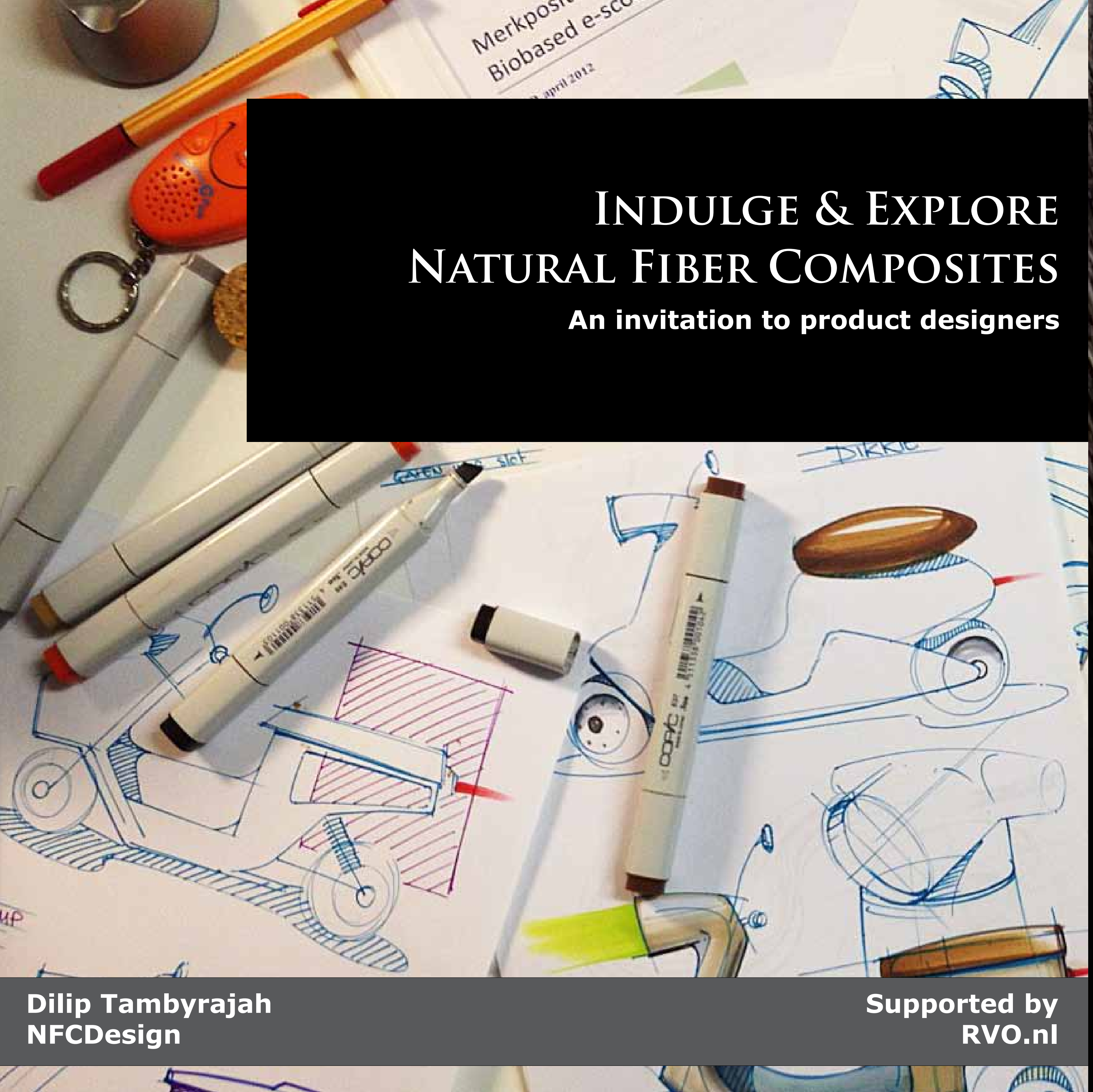

INDULGE & EXPLORE NATURAL FIBER COMPOSITES

An invitation to product designers

Dilip Tambyrajah
NFCDesign

Supported by
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Natural Fiber Composites Design

Product design-oriented knowledge platform

Product designers can contribute in a major way to accelerate the development of natural fibre composite applications in the Netherlands and elsewhere. It is expected that the use of renewable raw materials can provide an important impulse to sustainable societies. Based on renewable materials Natural Fibre Composites can provide an alternative for many synthetic materials. They can ease the increasing pressures of raw materials scarcity. The use of Natural Fibre Composites will contribute towards Biobased economic development and Circular Economies.

RVO.nl supports the knowledge network - NFCDesign Platform - in order to encourage the use of biobased materials such as Natural Fibre Composites in product design and industrial activities. NFCDesign is a platform where industry, product designers, academia and government agencies can meet to share and exchange knowledge and expertise on this subject. Product designers and others are very welcome to join the NFCDesign platform.

The key objectives of the NFCDesign platform are:

- √ **Ideas:** generate ideas to accelerate market developments of Natural Fibre Composites.
- √ **Inspiration:** inspire product designers to consider the use of Natural Fibre Composites in their design decisions.
- √ **Information:** develop initiatives to make information on Natural Fibre Composites accessible for all stakeholders.

www.nfcdesign.org

PREFACE

As an enthusiastic catamaran sailor I would love to break the waves with the Flaxcat, the world's first large construction using flax, built to withstand immense mechanical pressures. It is made of natural fiber composites and shows the strength and versatility of this material.

Natural fiber composites (NFC) use the force of nature. Natural fibers are a small wonder in themselves, as you will read in this book. Combined with a matrix or resin they can be as strong as steel, as smooth as ice and usable in any form the designer thinks of. With the advantages of a renewable and biobased source.

Stimulating the biobased economy is one of the goals of the Dutch government. The Netherlands Enterprise Agency works on this subject in several manners. One of them is the support of the platform Natural Fiber Composites Design (NFCDesign) in the last five years by the Environment & Technology Programme on behalf of the ministry of Infrastructure and Environment. In this platform designers, entrepreneurs and knowledge institutes networked in meetings on this subject. They were introduced to and inspired to work with this rather unknown material.

Although some forms of NFC were used more than hundred years ago, the rise of the plastic industry put NFC into a dark corner of the shelf. With this book we hope to put the spotlight on the advantages of this material again and inspire designers to apply it in their products. By leading you through the labyrinth of different fibers, matrixes and techniques this book gives you a lot of background knowledge and examples of the endless possibilities of natural fiber composites, from guitars to electric scooters.

Enjoy reading!

Bart Tonnaer

Manager Industry, Agriculture and Finance
Netherlands Enterprise Agency

The Netherlands Enterprise Agency (Rijksdienst voor Ondernemend Nederland: RVO.nl) encourages entrepreneurs in sustainable, agrarian, innovative and international business.

01

INTRODUCTION

> Do you want to spend
> the rest of your life
> selling sugared water or
> do you want a chance to
> change the world?

Steve Jobs

Introduction

The objective of this book is to provide a glimpse into the world of Natural Fiber Composites especially for product designers. It is intended as a preliminary exploration of the broad area of Natural Fiber Composites (NFC). NFC is a truly multi-disciplinary domain and therefore it is a challenge to cover in depth all the related areas without making it complicated for the non-technically oriented reader. This book is certainly not a technical manual on NFC nor is it a text book or a scientific discourse of the subject. It is based on sound science and current industrial practices. There are literally thousands of academic publications, many project reports and text books that provide detailed information on composites and even NFC. The interested readers could refer to these publications that are already freely available.

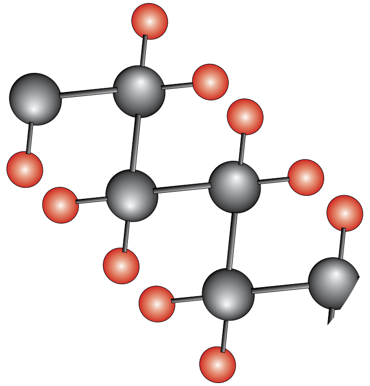
This book is richly illustrated to inspire the reader to appreciate the different types of products that are or can be made from NFC. Also to get a feeling of the diversity of this category of material. The objective is to indulge and hopefully inspire the reader towards action: that is consider NFC in their material choice in the design process; even to make NFC products in their garage.

NFC has to deal with two totally different worlds of materials. One key material is Natural Fibers - the reinforcing part - and the other is the polymers - the binding part - also commonly referred to as the matrix. The book will attempt to equip the reader with sufficient background information on NFC in an easy to digest manner so that he or she could start the exciting journey into the fascinating world of natural fibers combined with polymers to form NFC.

Before proceeding further a brief explanation is needed into three specific issues related to this book. The first issue is why produce yet another book when there is already so much information on the subject? Secondly, why NFC as a specific category of material? And thirdly, why are “product designers” specifically intended as the audience of this book?

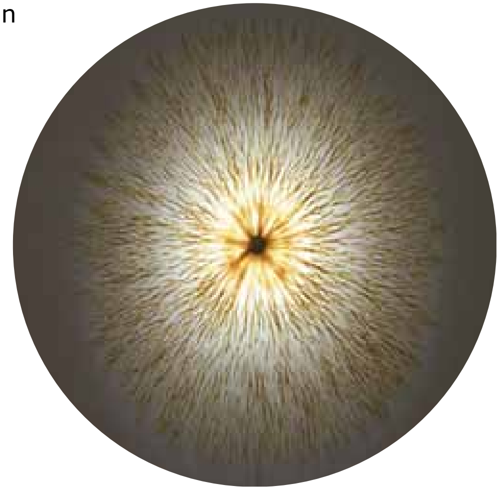
Why yet another book?

The observation is that publications on composites generally and NFC specifically tend to be rather technical. As mentioned earlier in this introduction, NFC is a multi-disciplinary domain. The polymer world is also divided with its own jargon and peculiarities. It is a chemistry subject, not a favorite of everyone. The other key part is natural fibers and renewable materials.



It is about agriculture, botany and biochemistry. An area lost to the urbanized population, with romantic ideas of rural life but ignorant of the complexities of the international agri-business and biobased economic developments. Emerging as the Biobased economy. Composites development and research generally tend to be dominated by engineers, especially from industries such as aerospace and automotive. In aerospace the focus is on structural parts where light weight, strength and stiffness are important engineering considerations. So for the lay person the subject NFC tends to be too complex and may even “put off” potentially interested parties. As far as NFC is concerned, like most of innovation related activities, there has been much talk and less action.

This is the key reason to write this book with many illustrations and pictures. Design considerations with NFC do not have to be focused, even become obsessive, about light weight and strength. After all we do not plan to send all man-made objects or artifacts to the moon! The objective of this book is to provide necessary and sufficient background information so that the reader can understand the wide range of materials involved and variety of technologies or processes used to make NFC based products also for daily use. And to do this in an illustrative way.



Why the focus on natural fiber composites?

NFC could contribute towards increased use of renewable materials such as natural fibers and accelerate developments towards biobased economy, a route towards sustainable societies. In the recent past the polymer industry has increased its efforts to produce polymers based on renewable materials. Therefore composites could become more and more bio-based. The ultimate objective must be to make composite materials using 100% renewable sources based on short carbon cycles. This can contribute towards sustainability and lessen the dependence on fossil/petro based products.

The international composites market in 2012 was estimated to be EUR 77 billion in value and 8.7 million tons in volume. The current NFC market in volume, in a most optimistic estimate, could be less than 150.000 tons per year, a tiny fraction of the composites market. Reliable statistics are not available but most of NFC is used in Europe and particularly in the highly competitive and technologically demanding automotive industry. The NFC estimates exclude Wood Plastic Composites (WPC) which is dominated by the USA and China markets. The global production volume of natural fibers such as Abaca, Coir, Flax, Hemp, Jute, Kenaf and Sisal, which are the candidates for NFC, is estimated at some 9 to 10 million tons per year. This means that the availability of natural fibers is certainly not a constraint for further development of NFC.

Why product designers as the target audience?

Finally the question is why "product designers" as the target audience to introduce the subject of NFC? The answer to this is rather straightforward. Product designers, be it industrial product designers, craftspersons or even artists, could capture the imagination of potential users by infusing aesthetic aspects into a product. Create products with personality. For example an aero space engineer is generally focused on light weight and strength, for understandable reasons. But the excessive obsession could blind creativity and inhibit an open mind to other solutions. NFC can be used in the interior of air-planes for instance but this option is often neglected because of the narrow engineering focus on structural parts.

Even though NFC has been around for several hundreds of years, in the recent industrial context the use of this material by industry has been rather slow. There are several industry political reasons for this, *including the dominance of plastic materials since the early 50's*, which will not be dealt with here any further. It is believed that product designers could play a crucial role in accelerating the market exposure of NFC by considering the material in their product design process or make in their own facilities small number of products based on NFC. In addition to industrial products NFC could also be used in arts and crafts with high aesthetic appeal. Natural fibers and resin have been combined to create works of art. The assumption is that product designers with creativity and open mind can produce aesthetically attractive and functional products. The ultimate objective is large scale adaptation and use of NFC in products in all segments of the economy.

Reading guide

This introduction briefly outlines the objectives of this publication. It also deals with the reasons for choosing NFC as a material category. In chapter two product design and materials selection considerations are presented. The plea to product designers is to take a holistic approach to material selection and not be to restricted by the limited mechanical properties, generally propagated in NFC research.
An introduction to composites is presented in chapter 3. It can be seen that NFC offers several combinations of natural fiber pre-forms and polymer matrix options. Chapter 4 shows the wide range of products that can be made with NFC. The products are for industrial as well as consumer markets. The chapters 5 and 6 deal in a concise manner, the two parts of NFC, namely the natural fibers and the polymer matrix. The natural fibers presented are Abaca, Coir, Flax, Hemp, Jute, Kenaf and Sisal. These fibers were selected mainly because they are available in large quantities and the global supply chains are well established. However, unlike the man-made fibers for composite applications the natural fiber preforms are still in development. Rapid progress is being made to serve the composites markets with advanced textile architecture for demanding applications. Chapter 7 provides an overview of some processes and technologies that has been developed over several decades by the composites industry. It is intended to provide product designers with a basic understanding of the different NFC production methods. Finally in the appendix additional information is provided as reference material on NFC.

02

MATERIALS & PRODUCT DESIGN

Post-Plastic Era

"Young designers have to understand that design is not art nor must it be fashion. It must be their ultimate goal to find new solutions to real problems.

On the political side of our work we need to overcome the damage of production, recognizing the mistakes we have made."

Phillippe Starck, in an interview with Designboom

PRODUCT DESIGN AND MATERIALS

The word Design has many meanings. The meaning of product design is also not as straight forward as it may seem. The context, the tangible and the intangible aspects could determine the true meaning. In designing an object, say a vase for flowers, the word "design" could have a specific meaning, it could be a product design in the context of Industrial Product Design if millions of vases are to be produced or it could be an object of art, in the context of Arts and Crafts, if just a single vase is to be made by hand to be exhibited in a museum. Design seems to suggest some "intent"; it can be action oriented. It is a noun, a verb or even an adjective. Design can be systems oriented but also a single object. The academics are unable to arrive at a common understanding of what design is.
So for practical reasons in this publication the use of the word design only refers to the design of objects made-by-people using Natural Fiber Composites (NFC) material in particular, both for large volume industrial products and for "arty products" with limited quantity or editions. The objective of this publication is to appeal to both schools of product design.

It is recognized that there are different approaches to "Product Design". For example in Industrial Product Design the intention could be to design products for mass production. In the "Arts and Crafts" approach the production could be just 1, 100 or even 1000 pieces. The differences in emphasis on functionalities and quantity could mean that both approaches would apply different methods and tools. In a highly simplified comparison the differences between Industrial Product Design approach and the Arts & Crafts are shown in table 2.1.

It is challenging to present a material like NFC to both groups as several issues should be reconciled to be appealing to both disciplines. It is not the intention to approach the subject from a "hard-core industrial design engineering" perspective or on the other hand an "over the top arty design" focus.

The International Charter of Artistic Craftsmanship by World Crafts Council - Works of artistic craftsmanship include:

- √ Creations, production and works of high aesthetic value, whether inspired by forms, models, decoration, styles and techniques that are traditional or historical, or the result of individual creative development and of personal and artistic forms of expression;
- √ Works which are mainly carried out using manual techniques, at highly professional technical level, using equipment, but excluding wholly mass-produced works; separate mechanised or automatic work stages are allowed, using innovative techniques and high-technology instruments;
- √ The definition of artistic craftsmanship also covers works of restoration, designed to conserve, consolidate or restore works of art, or objects of architectural, archaeological, ethnographic, bibliographic or archival heritage.

TABLE 2.1: Simplified comparison of industrial product design and arts & crafts

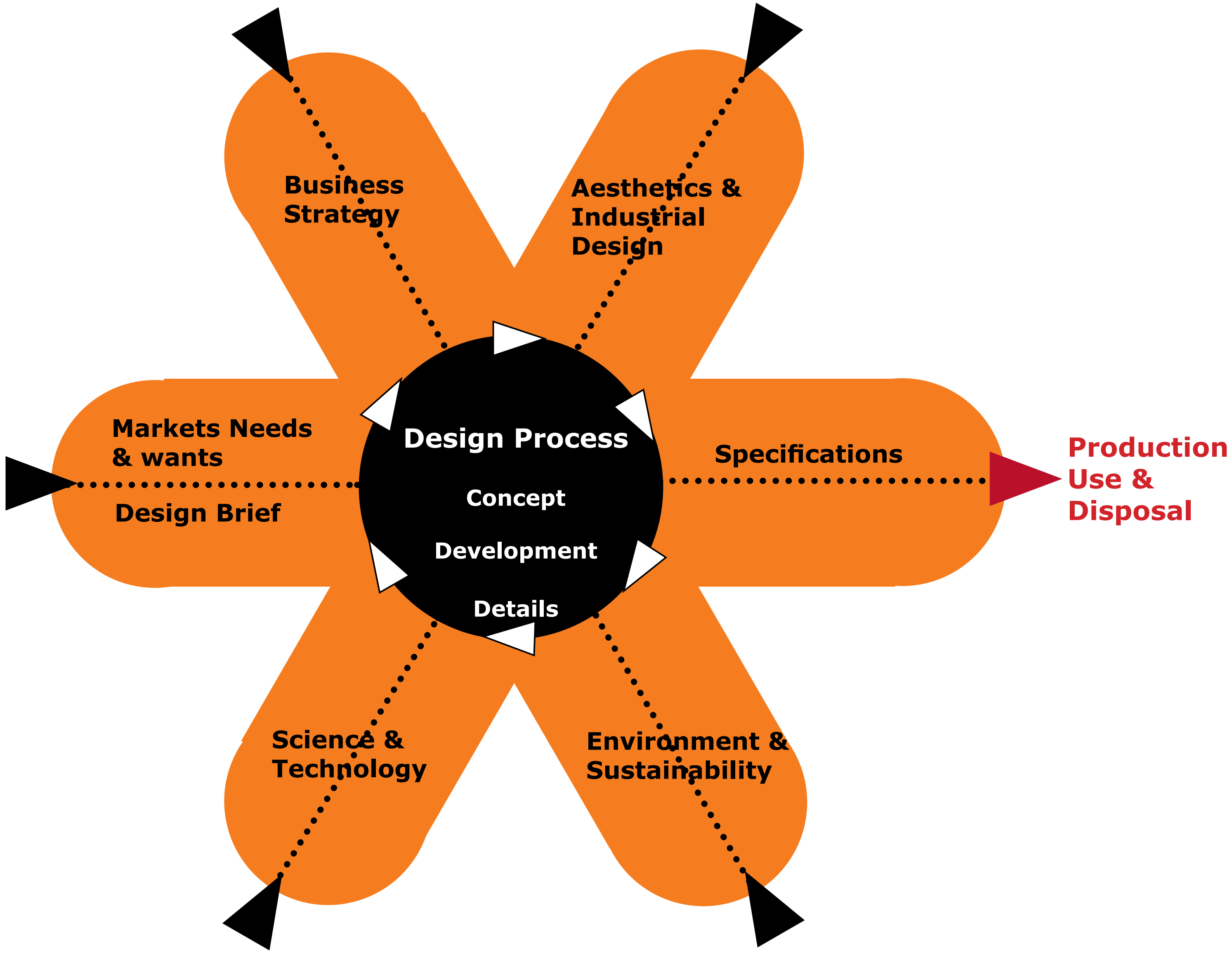
INDUSTRIAL PRODUCT DESIGN approach to the creation of objects	**ARTS & CRAFTS** approach to the creation of objects
The object created must have utility or functionality.	The object does not necessarily have utility other than being an object of desire.
The claim is that the steps involved in creating an object (product) is biased towards rational processes and methods.	Total freedom of creation but could structure the activities according to preferences
The discipline emerged (mainly in Europe) as the consequence of the European industrial revolution. Mainly the division of task in a chain of activities related to manufacturing. Manufacturing also implies producing objects in large numbers for larger number of users.	The object mainly manufactured or created by a single person, the "artist" or "craftsman". The number of objects produced is relatively small or even limited intentionally.
Is engineering biased, where strict engineering principles apply. Strive towards optimization.	Skills and aesthetic aspects are important, even provocation could be the objective
Mostly mechanized production	Mainly manual production

MATERIAL SELECTION IN PRODUCT DESIGN

Natural Fiber Composites (NFC) is about the use of natural fibers and polymers. Both basic materials are presented in some detail in chapter 5 and 6 of this book. The focus of this chapter is to draw attention to materials in product design and it is not about material selection *per se*. The hope is that designers would consider using NFC in their product design process. Academics such as Mike Ashby et. al. have already written extensively on materials and material selection methods and the interested reader could refer to their books. Figure 2.1 illustrates the interactive and continuous process of product design.

The product design process could be triggered from any one of the factors i.e. from a market need or want, business strategy, aesthetic motivation, environment & sustainability considerations or technology & science push. In academic education students are often taught that product design should start by first identifying the needs and wants of consumers. This does not have to be the case. In real business products could be launched, motivated by several reasons and consumers do not have to be a part of the decision process at all. As the word goes: consumers consume "what is given to them". To paraphrase Steve Jobs "people do not know what they want until you show it to them". Jobs has been successful many times with this approach but also had some failures. Consumers could be erratic and they can determine if a product is successful, in monetary terms, in the market place or not. But for some product designers success is more than just monetary return. For example success is when the product is taken into the collection of a reputed museum or generates publicity in the media. The hope is that this book can stimulate product designers to seek success in the markets but also to generate public awareness for the use of a renewable materials such as natural fibers.

FIGURE 2.1: DESIGN PROCESS & INPUTS



Source: M. Ashby and K. Johnson (2010), Materials & Design

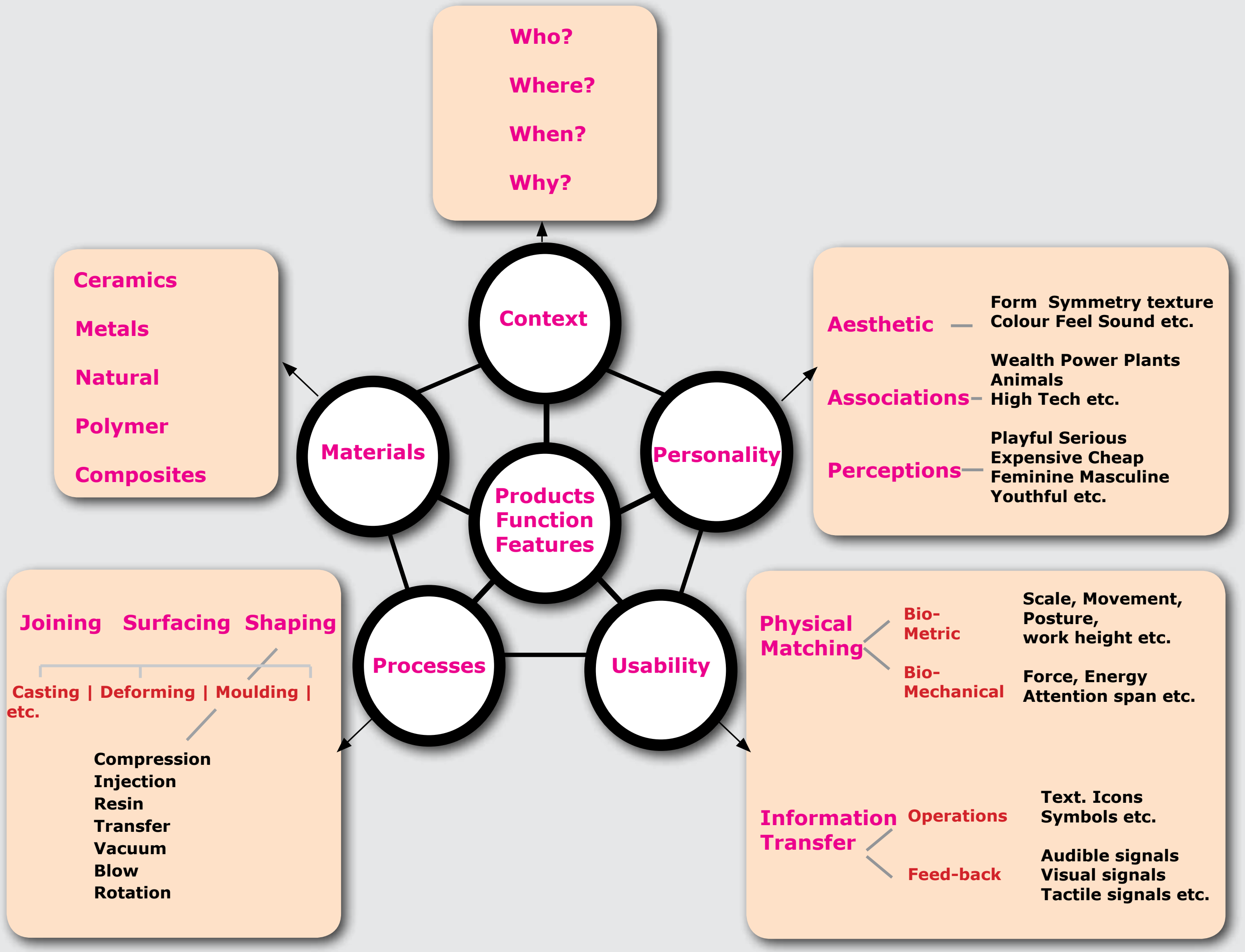
The focus of material properties: depends on who is looking at it.

Most of the traditional composite research is conducted by engineers working in areas such as aerospace, mechanical, chemical, marine, materials sciences etc. So the emphasis is mostly on the physical and engineering properties such as strength, stiffness, impact etc. The sensorial properties (e.g. look, touch, smell & sound) can be equally important in product design. Often this aspect of the product - human interaction - tends to get neglected. These soft aspects are not on the radar of hard core engineers and chemists. When it comes to a renewable material such as natural fibers, in addition to the above mentioned engineering disciplines, agriculture and botany are also involved. Open minded communication will certainly prove beneficial when these disciplines have to collaborate in a truly multidisciplinary subject such as NFC. Industrial product designers generally tend to cover all the aspects related to materials. Product designers with an arts and craft education tend to focus more on the intangible and the sensorial aspects of materials. Narratives and story-telling can be an integral part of their product. Increasingly the end users of products are beginning to appreciate the stories and narratives behind the materials, production and the products. Hence a holistic approach could increase the chances of a products success.
These differences in focus do not necessarily have to be negative or incorrect.
The beauty of a material for an aerospace engineer could be in its lightness, its strength or its stiffness. For a product designer with an arts and craft background the beauty of the material could be in its origins or its tradition of use. The "products personality". The key point is these two approaches to product design will create products with different "values and meanings".

Linkages of properties and aspects of materials in products.

The material selection process consists of several inter-dependent aspects. In an engineering design situation engineering methods, rules-of-thumb and past experiences could guide designers. Even design "habits" could play a decisive role. However, the situation is different when it comes to products that have a high level of consumer inter-action. Here the process could become complex due to the various combinations and interactions of products characteristics. The inter-dependencies could sometimes result in iterations of the material selection, if the process is assumed to be rational. In addition in branding consumer products the product personality needs to be skillfully created by business strategists along with product designers.
Figure 2.2 illustrates the different aspects of that needs to be considered in the product design process.

FIGURE 2.2: Dissection of product character

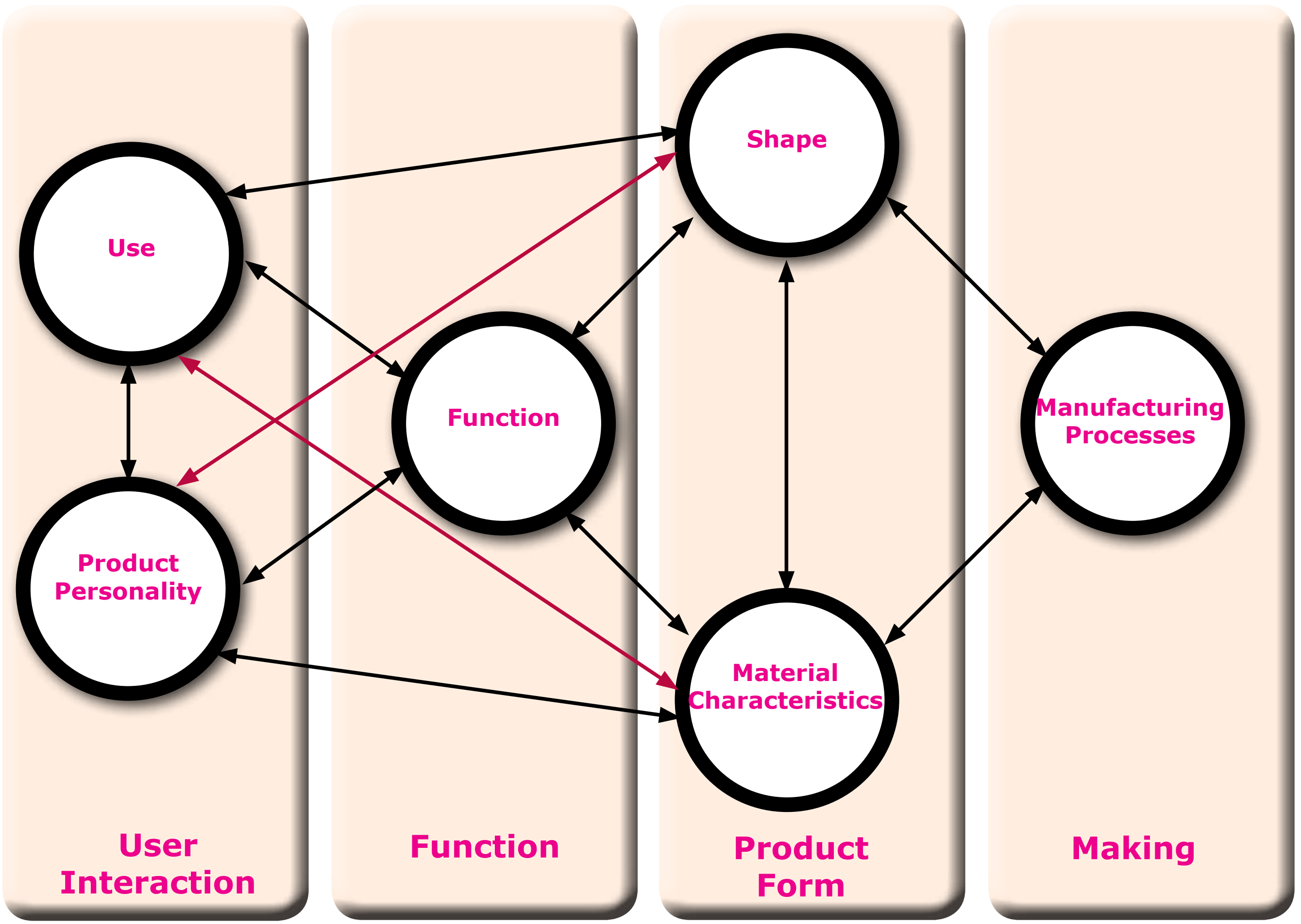


CONTEXT: Defines the mood or intentions. **MATERIALS & PROCESSES:** Create the flesh and bones. **USABILITY:** the interface and interaction with users. **PERSONALITY:** the aesthetics, association & perception creates the products Personality.

Source : M. Ashby (2004) - Materials & Product Design

The role of materials and their selection remains a diffuse aspect of the product design process. It is irrational or preference based or could be systematic. Figure 2.3. shows the typical aspects involved that could play a role in material selection and their inter-connectedness. The model shown is a typically industrial product engineering oriented approach. This book is not about the analysis of the product design methods or material selection process per se. In the context of NFC and natural fibers the key aspect could be the "Product Personality" and "Materials Characteristics". However elements such as "shape", "function" and "use" could also be used as hooks to design products that could "tell a story". In this respect the question is if the materials used can enhance the meaning of products?

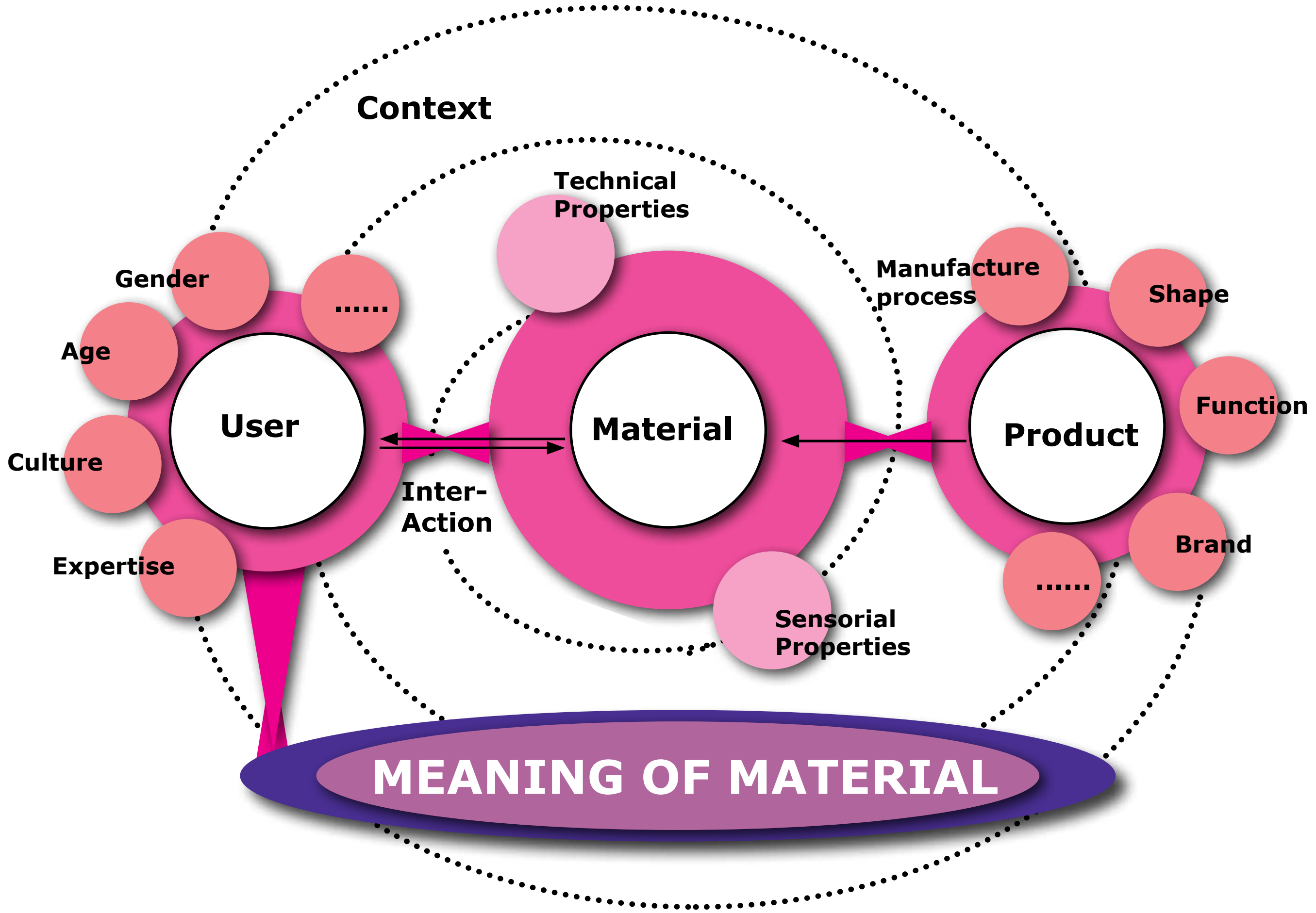
FIGURE 2.3: Considerations in the Material Selection Process



Source: Ilse van Keesteren (2008) Selecting materials in product design

Some researchers have explored the subject of the meaning of materials. Here issues typically explored are how materials can enhance the meaning of a product or how materials can gain added meaning due to the use in products. Figure 2.4. shows a Model of the Meaning of Materials. In an extreme case the ambition could be to design a product where ***"the material is the core of the product personality".***

FIGURE 2.4: Meaning of Materials - Linkages of User, Material & Product



Source: Elvin Karana (2013) Meanings of materials

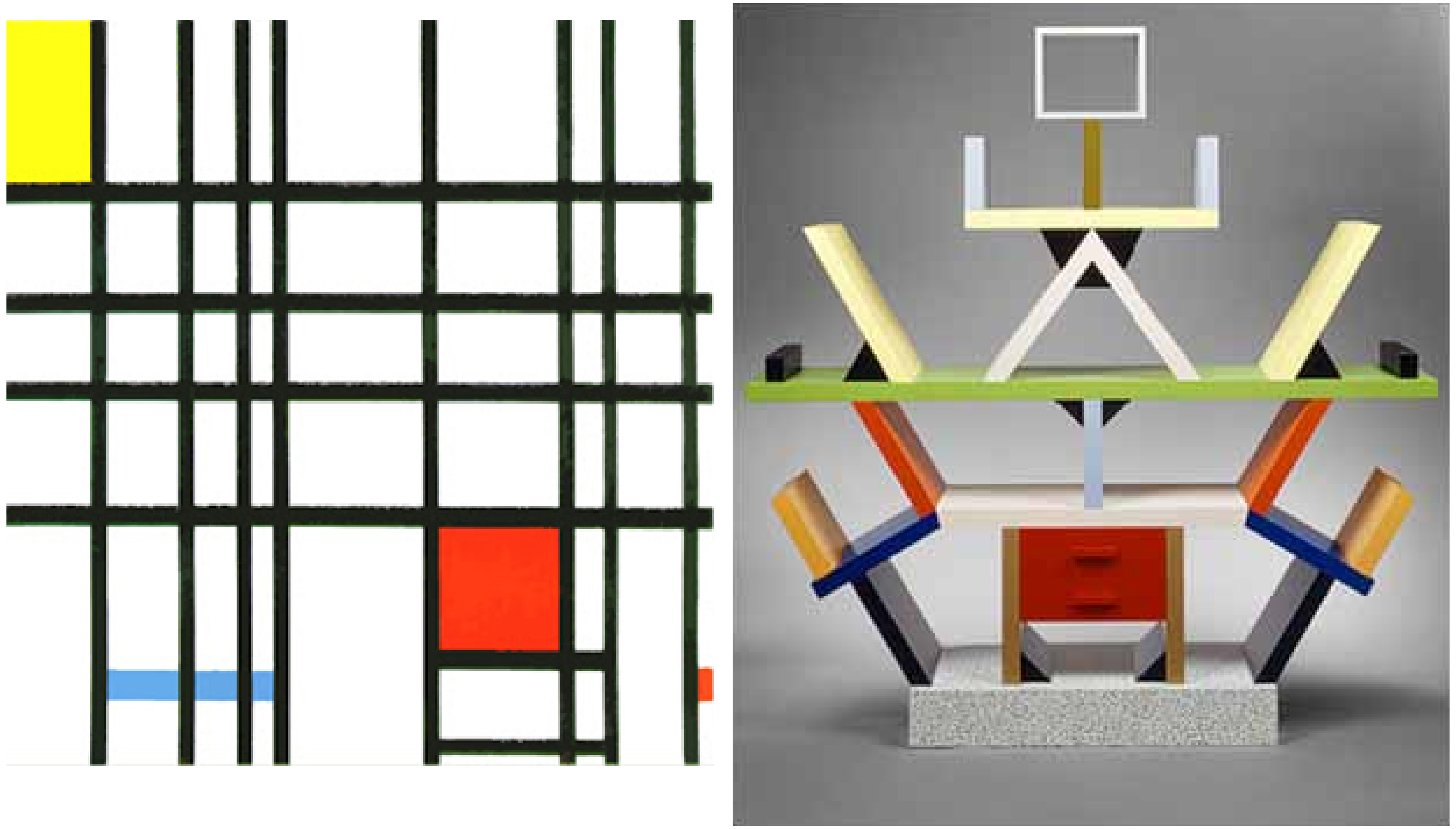
Table 2.1: Some perceived attributes of products with opposites

Perception (with opposites)	
Aggressive	Passive
Cheap	Expensive
Classic	Trendy
Clinical	Friendly
Clever	Silly
Common	Exclusive
Delicate	Rugged
Disposable	Lasting
Dull	Sexy
Elegant	Clumsy
Extravagant	Restrained
Feminine	Masculine
Formal	Informal
Hand-made	Mass produced
Honest	Deceptive
Humorous	Serious
Nostalgic	Futuristic
Mature	Youthful

Table 2.2: Some aesthetic attributes of materials

Senses	Attribute
Touch	Warm
	Cold
	Soft
	Hard
	Flexible
	Stiff
Sight	Optically clear
	Transparent
	Translucent
	Opaque
	Reflective
	Glossy
	Mat
	Textures
Hearing	Muffled
	Dull
	Sharp
	Resonant
	Ringing
	Low pitched
	High pitched

It seems one of the major shortcomings of design with renewable material, such as natural fibers, is that the various design schools have not succeeded in establishing a specific coherent design style, that is recognizable and easily identifiable for instance as Bauhaus, Art-Deco, Memphis or even attempt to position renewable materials based products in a post-modern context. Product designers have not progressed beyond the rhetoric of EcoDesign. The recent interest in bio-mimicry actually is old school. Sustainability Design, Cradle-to-Cradle, Nature inspired Design and similar concepts have really never established into a coherent style of product design. The challenge is to have a group of product designers, who are committed to creating the movement. This has been one of the motivating factors to establish the NFCDesign platform. This can be highly ambitious but not impossible to achieve.



Recognizable as styles but different in concept?

03

NATURAL
FIBER
COMPOSITES
1 + 1 = 3

2 + 2 = 4
2 + 2 = 5
2 + 2 = 3

'You are a slow learner, Winston'
said O'Brien gently.

'How can I help it? he blubbered.
'How can I help seeing what is in front
of my eyes? Two and two are four'

'Sometimes, Winston.
Sometimes they are five.
Sometimes they are three.
Sometimes they are all of them
at the same time. You must try harder.
It is not easy to become sane.'

1984, George Orwell

TYPES OF COMPOSITES AND REINFORCEMENT

Very often product designers who wish to explore the potential of NFC, ask:
"I want to design a product with natural fiber composite (NFC). Where can I get the material?"
It may be useful to recognize that NFC is, from a technical view point, a highly multi-disciplinary field, with expertise needed from polymer chemists, biologists, product designers and engineers of various sorts. Most often a single company would not have all the expertise in house. Especially in the area of natural fibers, for use in composites, the expertise is limited. So the interested product designer should have patience and look for the right type of support in order to make his or her idea a reality.

This chapter is mainly about composites in general and the types of fiber (reinforcement) architecture. It is intended to prepare the eager product designer and equipping him or her with the basics of composites fiber architecture and reinforcement of NFC. It is emphasized that this chapter is only an introduction to this topic.

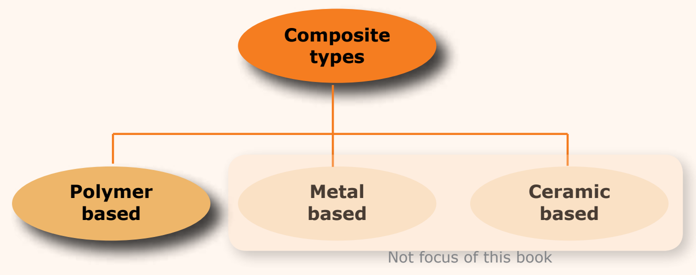
What is a composite?

Basically a composite is a combination of two or more materials with different properties.
They retain their individual property but the combination could exhibit improved properties as a whole.
Aiming for a 1+1 = 3 effect.

Classification of composites

Composites can be classified according to the matrix and the complementing material used. The complimenting material in the present case is Natural Fibers. Figure 3.1 provides an overview of composites.

Figure 3.1: Type of composite



The focus of this publication is on polymer based composites. Ceramic and metal based composites will not be addressed here.

Characteristics of polymer matrix - fiber composites

Very often the literature tends to focus on the mechanical properties of composites. The idea is that composites should show (not limitative):

√ High specific strength
√ High specific stiffness
√ High impact resistance
√ Light weight
√ Good abrasion resistance
√ Good corrosion resistance
√ Good fatigue strength
√ Design flexibility in shapes & form

In addition to mechanical properties the aesthetic properties such as look, feel and sound could be of importance in product design. The material can also be a part of the products brand image.

Increasingly the environmental aspects of composites are gaining attention. As composites made of biobased materials are becoming readily available.

Composites can also exhibit some less desirable characteristics like:

- Temperature limitations for processing.
- The properties such as strength, stiffness etc. could be different in different directions. Therefore composites can exhibit anisotropic properties. The anisotropic properties of composites could pose problems when there are multi-directional forces acting on the object. An isotropic material has uniform properties in all directions.
- Properties could be dependent on the manufacturing process.

However, by appropriate design the impact of these limitations can be reduced.
For example the anisotropic characteristics could be reduced by the fiber architecture or by stacking/layering.

The factors that effect the properties of composites

The technical factors that should be considered when using natural fibers as reinforcement are:

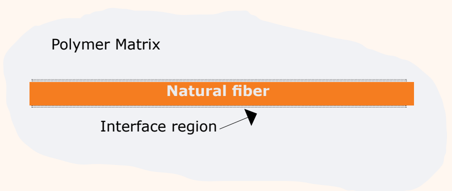
√ the properties of the natural fibers.
√ the surface interaction between the natural fibers and the polymer matrix. Often referred to as Interface region.
√ the arrangement or orientation of the natural fiber reinforcement.
√ the amount (volume fraction) of the natural fibers used.

It should be emphasized that in addition to the technical factors other product design aspects such as "look, touch & feel" could also play a role in composites. However the products technical or engineering characteristics and requirements should be met to ensure the reliability and function of the material.

Interface adhesion between matrix and fibers

The bonding between the natural fiber and the polymer matrix plays an important role in determining the properties of the composite. In simple terms it could be imagined that there is a zone in which the properties of the fibers transition to the properties of the polymer matrix and visa versa. This transition zone must function optimally so that each part does its job properly. Designing this Interface, see Figure 3.2, is very important to achieve the best possible properties of the composite.

Figure 3.2: Interface between natural fiber and polymer matrix



Optimal adhesion between fibers and polymer matrix will lead to superior properties of NFC

But why is interface in NFC a concern? One of the properties of natural fibers is that they can attract moisture i.e. natural fibers are said to be strongly polar and hence hydrophilic. This characteristic is mainly caused by the different biochemical components in the natural fiber itself. On the other hand the man-made polymer matrix tends to be Apolar and generally hydrophobic. So essentially it is a compatibility problem between natural and man-made materials. Natural fibers themselves are composite materials consisting of different polymers and fiberous structures. But nature has resolved the interface issues elegantly. The natural fibers are able to optimally fulfil their functions within the plant.
Over the years researchers have recognized and proposed strategies to deal with this compatibility issue in NFC. The key strategies are to modify the surfaces of the natural fiber or to supplement the polymer matrix properties with additives to enhance the adhesion between the two materials.

Physical treatment, such as Corona and Plasma treatment attempt to modify the fiber surface area so that the bonding with the polymer matrix is improved. Mercerisation is an old method for treating textile fibers. It is also possible to follow a chemical route. The simplest method is to treat the natural fibers with a chemical such as an alkaline (e.g. 5% NaOH) solution for a certain amount of time. However, if not done correctly, such treatments can weaken the overall mechanical properties of the natural fibers because lignin, the natural binding material or matrix in natural fibers, could also be weakened. Acetylation is another method to make the surface of the natural fiber hydrophobic.

An easier approach is to supplement the polymer matrix by using compatibiliser or coupling agents. Maleated coupling is a commonly used method. The addition of a small percentage of a coupling agent could improve the adhesion between the natural fibers and the polymer matrix. Typical coupling agents are Anhydride-polypropyerlene copolymer (MAPP) and Silane. The key issues would be to find the right combination of coupling agent, natural fibers and the polymer matrix. There are tests that could determine the degree of bonding between the natural fibers and the polymer matrix. These include fiber pull-out tests, micro bond-debond tests and micro indentation tests. As the interface issue has been the concern of researchers and academics for several years, the interested reader can refer to a rich volume of literature on the subject.

For some advanced applications improving the properties, at additional costs, could be interesting. But not in all cases. Interface challenges should not be a barrier to use NFC. Even without any additives or special surface treatment NFC based products can be produced. Most of the academic research is aimed at maximizing the properties of NFC, without questioning the real need of higher strength for example or the functional requirement of the product in question. Over-engineering, costs and time can be avoided when the material properties can be matched to the product specifications and need.

Arrangement of fibers in composites

The natural fibers can be placed in the matrix in different forms and ways. The vocabulary and even the theoretical concepts generally used have their roots in the man-made fiber reinforced composites industry. Some care is needed in using these terms to natural fibers.
The orientation and the dispersion of the fibers in the matrix play a significant role in determining the mechanical properties of the composite. In the present context, when reference is made to fibers, it means the “Preforms” or the derived products (semi-products) of fibers. Unlike man-made filaments/fibers, natural fibers have a finite length. However bundles of natural fibers can be processed to form yarns, slivers, tows and rovings that have very long lengths. The preforms of natural fibers can also be pre-impregnated or mixed (compounded) with a polymer. These pre-pregs or compounds can be purchased ready for further processing.

The (natural fiber) composites can be described in many ways. A common description is the form of the fiber part. They can be:

- Particulate reinforcement
- Flake reinforcement
- Fiber reinforcement.

For the sake of completeness particulate and flake reinforcement are briefly described. Fiber reinforcement is the key preform type discussed in this section because it has the most diverse range of semi-products of natural fibers.

Particulate reinforcement

It is assumed that particles, generally, do not to have long dimensions.
They could have the same dimension in all directions. In many composites particles can be randomly oriented in the matrix. Particles do not contribute to improvement of strength but could improve other properties. It may not be advisable to use natural fibers as particulate reinforcement, unless as a filler to reduce costs. This is because fibers naturally have a high length to diameter ratio that can be beneficial in composites.

Flake reinforcement

Flakes could have positive effect compared to particulate reinforcement because the dimensional geometry; they could exhibit equal strength in all directions. Potentially it is very difficult to exploit flake reinforcement in NFC due to the costs of producing natural fiber flakes.

Fibrous reinforcement

The key characteristic of fibrous materials in composites is the length (L) to cross-sectional dimensions or diameter (D). The ratio L/D is called Aspect ratio. Different natural fibers can have different aspect ratios. But within each fiber type itself the aspect ratio could vary. So the question is what is meant by “fiber length”?

Fibers used in composites are commonly referred to as “short fibers”, “long fibers” and “continuous fibers”. There is no internationally agreed nomenclature therefore these terms can be confusing and even misleading. For example if the natural fibers length in a Polypropylene (PP) based compound, used for injection moulding, is 0,2 to 2,0 mm then fiber lengths of 20-25 mm used in Long-Fiber-Technology (LFT) is considered “long”. Another example could be found in coir fiber non-woven (or random mats) production. In this preform fiber lengths lower than 100-120 mm would be considered short and 180-200 mm as long and maybe even problematic for non-woven production. Therefore the product designer should really seek further clarification when the terms “short and long” fibers are used.

In composites literature on man-made fibers such as glass fiber it is suggested that an aspect ratio (L/D) of more than 15 is needed for good strength and stiffness properties. This is the critical length of the fiber for a given diameter. For a fiber of 1,0 mm diameter the length must be above 15 mm for good strength and stiffness properties. The literature on natural fiber composites is not very clear about the aspect ratio of natural fibers in composites. This is because it seems these properties and rules have been determined for man-made material such as glass of carbon fiber. But natural fibers have totally different and varying structures. However, several natural fibers naturally have aspects ratio higher than 15. This is one of the reasons to claim superior properties of natural cellulose as reinforcement in composites.

Generally fibrous reinforcement would improve most mechanical properties of the matrix. The degree to which the fibers materials improve the mechanical or engineering properties would depend on factors such as:

√ the form of the fibrous material e.g. continuous or discontinuous.
√ the orientation of the fibrous material in the matrix i.e. random or oriented.
√ the aspect ratio (L/D), as in the matrix.
√ the type of natural fiber used i.e. abaca, coir (coconut), flax, hemp, jute, kenaf, sisal etc.

Fibers used with a very high aspect ratio are known as continuous fiber reinforcement and preferably they should be oriented. In this case the term Uni-Directional fiber reinforcement (UD) is used. Single strands of natural fiber could be used as oriented reinforcement. But if this is commercially and practically feasible is another matter. The single strands can be spun into low twist yarn and used as oriented fiber reinforcement. But some academics argue that the “twist” in the yarn could reduce the mechanical properties in comparison to the single strands of fibers. However there is conflicting scientific data on this debate due to the very complex nature of this subject and how the materials are used. An international agreement and harmonization of the NFC nomenclature could greatly reduce the ambiguity that currently seems to prevail. In this effort NFC community could focus on the natural materials themselves; not be distracted or try to imitate man-made fibers in an attempt to fit natural fibers into these concepts. Therefore terms such as continuous reinforcement are not used in the book. Because unlike mono-filaments of endless lengths of man-made fibers, natural fibers have limited length (e.g. 2/3 m). This means some form of twisting will be needed to produce “continuous” fibers. But of course all this depends on the applications. Where small dimensions (< 2/3 m) are needed natural fiber maybe considered “continuous”.

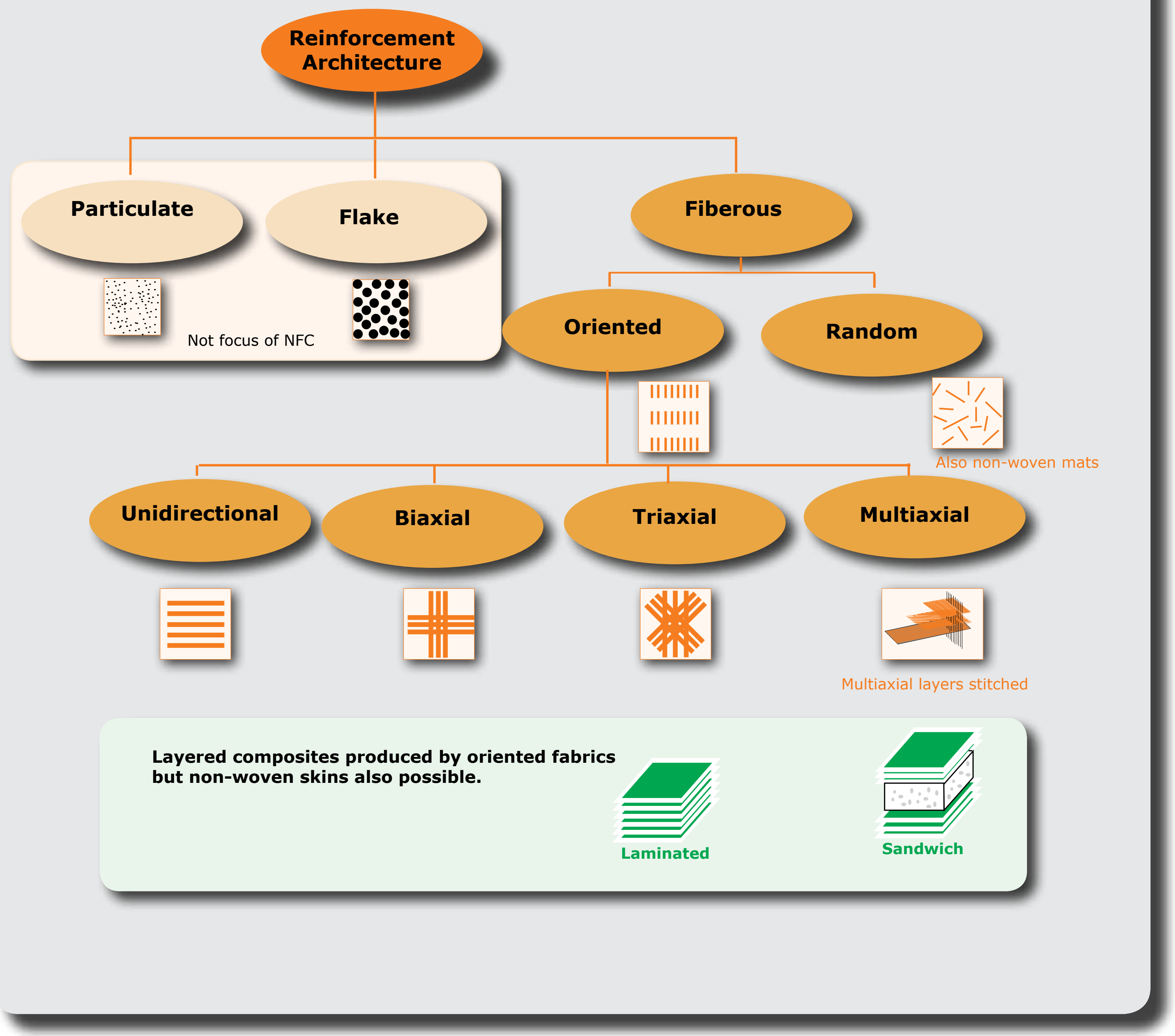
As far as NFC is concerned, at this stage of technology development and availability, using single oriented natural fiber strands could be difficult in terms of manufacturing and therefore costly. On the short term mass volume application could be limited. As fiber processing solutions are developed, on the long run, the cost of producing UD natural fiber preform could be reduced.

Random and discontinuous fibers, as short fibers, can be used in compounds. These natural fibers (abaca, coir, flax, hemp, jute, kenaf, sisal etc.) can be compounded with a wide range of polymers to form these prepregs.
The properties of these compounds will depend on:

√ the amount (volume) of fiber used.
√ the type of polymer matrix used.
√ the additives used.
√ how the compound is produced in the extruder.

Some examples of fiber reinforcements are illustrated in figure 3.3.

Figure 3.3: Type of composite reinforcement
(Simplified illustration - terms continuous and discontinuous fibers not used)



Unidirectional fabrics

In unidirectional (UD) fabric most of the fiber strands are in one direction. But a small amount of fibers (yarn in the case of natural fibers) will be needed to hold the fiber strands in place. Ideally the UD (say longitudinal) fibers should account for more than 80/85% of the fabric weight. The UD fabric would have very low crimp (waviness) of the fibers. UD fabrics can be produced with secondary fibers but also by using a resin/binder or other means to hold the fibers in place. The UD fabrics can be layered to form biaxial, triaxial and multiaxial configurations. The different layers with fiber orientations can be held together by stitching in the "Z-direction" i.e. through the layers. These fiber architectures are generally known as Non Crimp Fabrics (NCF).

Woven fabrics

The simplest weave is the Plain weave. This is also the most commonly used weave for fabrics. In the case of natural fiber, which uses yarns (instead of so called filaments/fibers as in man-made materials), the orientation is $0^0/90^0$.
The other types of commonly used weaves are Twill, Satin, Basket, Leno and Mock Leno.
The figure 3.4. shows the various weaves that could be of interest for NFC application. The main characteristics of the different weaves are summarized in table 3.1.

It is only recently that natural fiber textile architectures, particularly, for composites applications are being developed and marketed. The main development taking place with flax fiber and in some instances with jute and hemp fiber. When woven fabrics are stacked to form a laminate then the orientation of the material should be decided. The general notation of the stacking could be illustrated as shown in figure 3.5.

In some cases a mix of natural fiber fabrics could be combined with either glass or carbon fiber to achieve the required mechanical properties. These could be considered hybrid-composites.

Braiding

Braids are tubular fabrics produced by inter-twining (interlacing) yarns.
The braiding angle is an important parameter. Biaxial braided fabrics exhibit high torsion stability. However they deform under tension. Braids are used in composite parts such as masts, drive shafts, fishing rods and other tubular components.

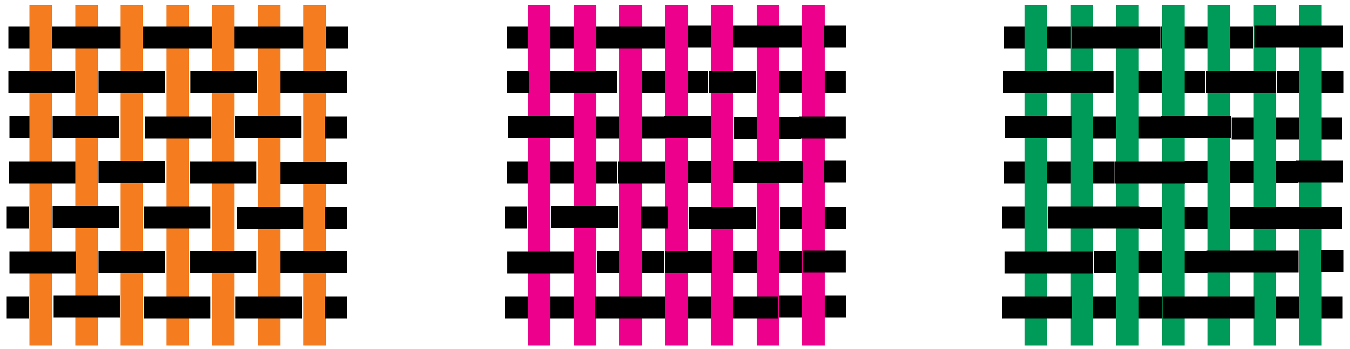
Knitting

In this process of fabric production yarns are inter-looped i.e. drawing one yarn over previous loops. There are several knitting methods, details of which can be found in the literature on textile production technology. At present knitted fabrics are not widely used in natural fiber composites.

The design parameters or properties of NFC

In this publication the properties of NFC are not provided because it can be misleading. Misleading because it is virtually impossible to provide data on all the possible combinations of polymer matrix and NF. Therefore in table 3.2. a list of typical mechanical properties are provided. The product designer should request the supplier or the manufacturer for specific details of the material to be used.

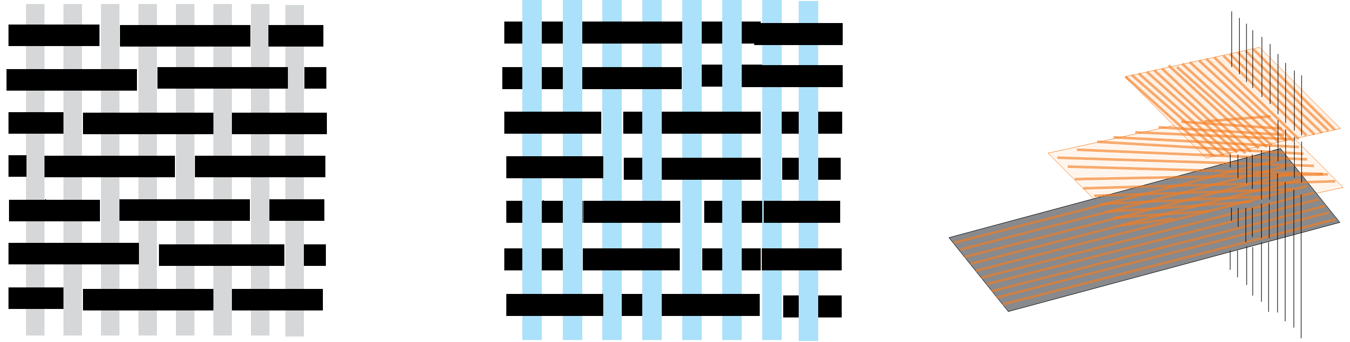
Figure 3.4: Different types of textiles weaves



Plain

2/1 Twill

2/2 Twill

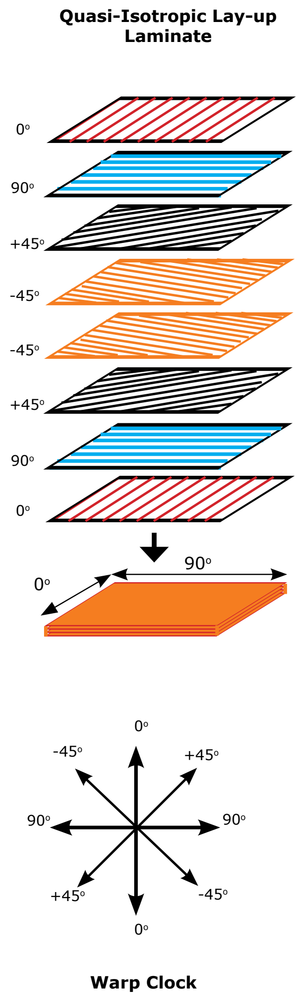


4 Harness Satin

2 x 2 Basket weave

Stitched layers

Figure 3.5. An illustration of textile layers or stacks for laminates



Some terms: Textiles and mat preforms

Structured textiles are used in composite technology due to the many possibilities of combinations and the wide range of applications. Generally in composites application the term textile preforms is used. This refers to fibrous materials that are arranged in a specific way, i.e. oriented, and sometimes preimpregnated with a polymer matrix. With the many possibilities of textile architecture, the creative product designers could explore a wide range of products that require strength and stiffness. The textile architecture could be exploited in the product design to enhance the aesthetics of the product concerned. In the context of composites the fibers are the load carrying element.
The terminology used to refer to the fabrics and reinforcement tends to be a mix of terms used in textiles technology and the traditional composites technology. So for clarity some common terms are briefly explained below.

Fibers: A generic term commonly understood for materials where the length is much larger than the diameter; a high aspect ratio (= L/D).

Filament: A single fiber (a term mostly used in man-made fibers; produced by extrusion or drawn) potentially very long and continuous. In natural fiber it can be a single strand of fiber, some refer to it as fiber bundle.

Tow: Untwisted bundle of (continuous) filaments, term mostly used for man-made materials.

Roving: Number of yarn (tows) in parallel bundles without or with very little twist.

Tape: Parallel filaments (maybe tows). Length greater than the width. Width much larger than thickness.

Yarn: A twisted bundle of fiber-strands or filament. Take note there is a whole vocabulary for twisted fibers i.e. slivers (low twist), threads, ropes, cords etc.

Woven fabrics: A planer material of inter-laced yarn or tows. They can be 2-D and 3-D fabrics of variety of fabric architecture, with different types of weaves.

Braiding: Interlaced yarn often in tubular shape. It is a process where two or more strands, yarns or tapes are intertwined in the bias direction to form an integrated structure.

Mats: A planer form of material or randomly oriented fibers i.e. Non-woven mats.

Warp: Yarn in the lengthwise direction.

Weft: Yarn in the transverse direction to the warp yarn. Also called Fill.

Crimp: In textiles for composites it means the waviness of the yarn. Non-crimp means yarns with very low or no waviness in the fabric.

Table 4.1: Comparison of Weave Type Properties

Property	Plain	Twill	Satin	Basket	Leno	Mock Leno
Stability	▣▣▣▣▣	▣▣▣	▣▣	▣▣	▣▣▣▣▣	▣▣▣
Drape	▣▣	▣▣▣▣▣	▣▣▣▣▣	▣▣▣	▣	▣▣
Porosity	▣▣▣	▣▣▣▣	▣▣▣▣▣	▣▣	▣	▣▣▣
Smoothness	▣▣	▣▣▣	▣▣▣▣▣	▣▣	▣	▣▣
Balance	▣▣▣▣▣	▣▣▣▣▣	▣▣	▣▣▣▣	▣▣	▣▣▣▣
Symmetry	▣▣▣▣▣	▣▣▣	▣	▣▣▣	▣	▣▣▣▣
Crimp	▣▣	▣▣▣	▣▣▣▣▣	▣▣	▣▣ / ▣▣▣▣▣	▣▣

Rating:
Excellent ▣▣▣▣▣ | Good: ▣▣▣▣ | Acceptable: ▣▣▣ | Poor: ▣▣ | Very poor: ▣

Source: SP composites handbook (1998)

Table 4.2: Typical engineering properties of composites

(Not limitative)

√ Strength Tensile, Flexural and Compressive
√ Stiffness Tensile, Flexural and Compressive
√ Elongation
√ Impact strength
√ Interlaminar strength
√ Fiber volume content
√ Density
√ Heat Deflection Temperature
√ Coefficient of thermal expansion
√ Hydroscopic expansion
√ ....

Random orientation

Non-woven fabrics

The textile preform can also be produced by non-woven methods. Here the fibers are entangled by various methods.
The common non-woven production include:

- Needle punch
- Thermal bonding
- Resin bonding

Natural fiber non-woven fabrics are relatively easy to produce in large quantities. They can be cost attractive for composite applications. However their mechanical properties, compared to woven fabrics, could be lower.

Short fibers in polymers

Technologies such as injection moulding, Long Fiber Technology use “short fibers”. The fiber is mixed homogenously as possible in the polymer matrix. A natural fiber and polymer mix, for example Jute/PP, in granule form can be produced for injection moulding. Or cut short fiber 10-20mm length could be used in Long Fiber Technology to be mixed with the polymer matrix to form a dough before being compression moulded. It should be noted that the natural fibers do not function as a filler but as a reinforcing material.

The type of polymer used for pre-pregs

As mentioned before prepregs are materials where the fiber and matrix are already mixed and ready to be used in further processing. In recent years natural fiber based prepregs are available in the market place. Technically all types of natural fiber can be used in prepregs.
In some instances different natural fibers, e.g. kenaf and hemp fiber, are mixed to produce nonwoven preforms and then impregnated with a matrix. These prepregs can be compression moulded to the desired product.

Thermoset prepregs

Depending on the product specifications and designers preferences these prepregs could be produced by a combination of woven and non-woven mats impregnated with a thermoset matrix. There is a wide range of polymers and additives that could be used in these prepregs. For example the Hemp/Kenaf Chair designed by Werner Assilinger is based on a non-woven mat impregnated with Acourdor resin (BASF) and then compression moulded (see chapter 4). The properties of the prepreg would depend on the matrix and the fiber preform used.

Thermoplastic prepreg

Earlier in this chapter one type of prepreg - the compound - was already mentioned. Natural fibers can be co-mingled with man-made polymers to produce yarns. These yarns could be preformed into different types of woven mats. In recent years oriented flax fibers have been used with a polymer backing to form unidirectional preforms. It is claimed that the UD fibers, due to the minimized twist could result in improved mechanical properties. Even though flax fiber based UD preforms are available in the market more developmental work is being undertaken to optimize the technical and commercial aspects of these products.

Table 4.3: Properties of Natural Fiber Composites

This table has been intentionally left blank!

Please see note.

Note on the "Properties of natural fiber composites"

Throughout this publication the key message is about the diversity of characteristics of NFC as a material. There are very many natural fiber preforms with which the polymer matrix can be reinforced. There are also very many natural fibers and fiber preforms, with different engineering properties that can be used in NFC products. Not to mention the wide range of polymer matrix and technologies that can be used to produce NFC parts. All this means that any table that pretends to capture the properties of NFC will only be very specific to a combination of materials and technology. The potential danger of presenting such properties is that incorrect conclusions could be drawn from a limited set of data. The author has resisted the temptation to present data that is too limited and does not do justice to the true potential of NFC as material.

The many combinations of natural fibers and polymer matrix materials and technologies provide a huge range of possibilities to tailor product shapes & forms, in combination with suitable production technologies and production volume that is cost effective.

The beauty of NFC is that the product designer has the flexibility to engineer the required mechanical properties and to create aesthetically appealing products that natural fiber architecture offers.

This is the reason for intentionally leaving table 4.3. - Properties of NFC - blank. It is intended to provoke and encourage the product designer to think critically about NFC and also to be critical of any data that is presented.

COMPOSITES: THE ARITHMETIC

Most of the composites theory is based on man-made fibers such as glass fiber. Therefore applying them to natural fiber based composites needs extra attention. Natural fibers themselves as they are extracted from the crops are composite materials. Nature has built in variability into these materials for known or even unknown reasons. Therefore the genius of the product designer would be in factoring this natural variability in the products design rather than trying to destroy what nature provides in an attempt to “homogenise”.
As mentioned in the introduction this publication is not meant as an engineering design guide on NFC. It is an introduction on NFC; the interested reader can refer to several excellent books on the engineering design of composites. However in this section a few simple factors on composite engineering design are presented so that the product designers can get an initial flavour of the subject.
Composites are about mixing two different materials, in this case a matrix and a natural fiber. The end result depends on several factors but from the materials side it is dependent upon the relative quantities mixed and the properties of the constituent materials.

For example the density of Polyester is 1,25 kg per dm^3 (deci-cubic meter or litre) and the density of Glass fiber is say 2,50 kg per dm^3. If they are mixed at 1,0 kg per material the resulting composite will have a density of 1,875 kg/dm^3.

This is the arithmetic middle of value of the two materials. The mixing is known as simple linear mixing.

The general expression for aligned fibers in matrix is:

$K = \alpha f \bullet Kf + \alpha m \bullet Km$,

where K is the property and αm is the volume fraction of the Matrix (polymer) and αf is the volume faction of the fiber.

If the fibers are not aligned in the 2 or 3 dimensions then a correction factor should be used. It is suggested that a factor of 1/3 be used for 2D and 1/6 for 3D non-aligned fibers in matrix.

The stiffness (E) is calculated by: $Ec = \alpha f \bullet Ef + \alpha m \bullet Em$

The strength (σ) is calculated by: $\sigma c = \alpha f \bullet \sigma f + \alpha m \bullet \sigma m$

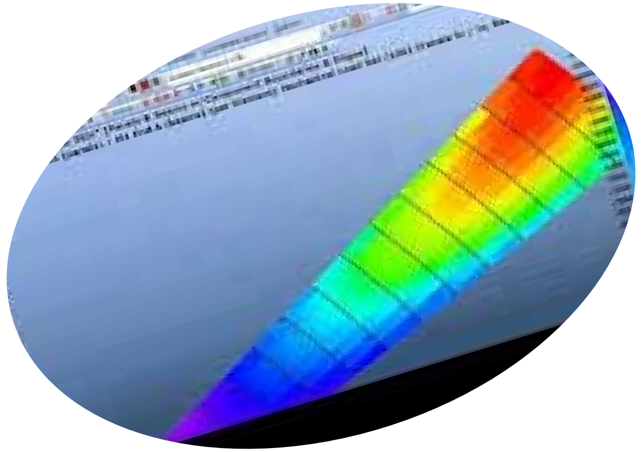
The density (ρ) is $\rho\ c = \alpha f \bullet \rho f + \alpha m \bullet \rho m$

The moisture content (M is weight units) is generally estimated by: $Mc = \alpha f \bullet Mf + \alpha m \bullet Mm$

In this case M is the weight and not the volume. It should be noted that the moisture content is dependent on the conditions, such as relative humidity, dry bulb temperature of the environment. The Moisture Equilibrium Conditions of natural fibers need to be taken into account when processing. This is the amount of moisture that a natural material would have in relation to the environmental conditions. This phenomenon could easily be understood for example by the expansion and contraction or swelling of wood. These are just a few examples of the composites properties. There are several other engineering properties of composites, such as porosity, the biochemical and physical properties of natural fiber, that are of importance in materials design.

Only a few simple expression are given so that the non-technical reader has some idea of the arithmatic for natural fiber and polymer matrix mixtures. Of course there are complicated calculation methods and models to engineer advanced composites based components and products. There are also simulation and mathematical techniques, such as finite element method, computational fluid dynamics, to estimate and predict the characteristics of NFC. These are not in the scope of this book.

As far as product design is concerned it is a matter of finding the right material for the application and balancing the appropriate properties. The material characteristics could be more than just the engineering properties only. The aesthetic character and the sensorial properties of NFC could be equally important in imparting personality to attractively designed products.



04

SEEING IS BELIEVING: NATURAL FIBER COMPOSITE PRODUCTS

> A lot of times, people don’t know what they want until you show it to them.
>
> ***Steve Jobs***

Be.e E-Scooter

Flax fiber combined with Bio-resin

Composite parts produced by vacuum infusion

Designed by:

Maarten Heijltjes & Simon Akkaya
Waarmakers Studio, Amsterdam

in cooperation with

Compositelab INHolland, Delft

NPSP

&

Van Eko

Be.e E-Scooter

Flax fiber combined with Bio-resin

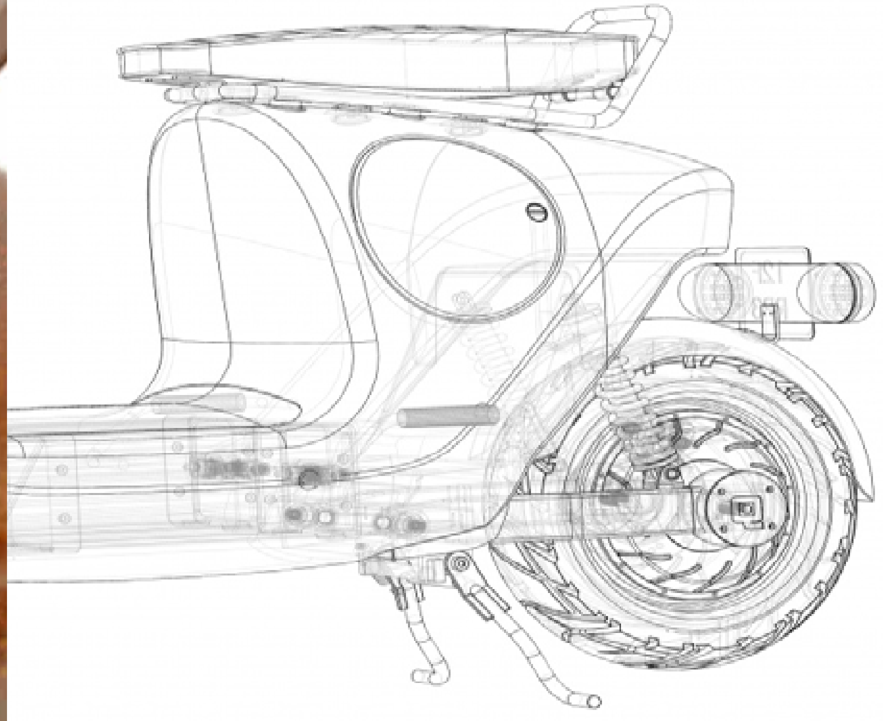
Composite parts produced by Vacuum infusion

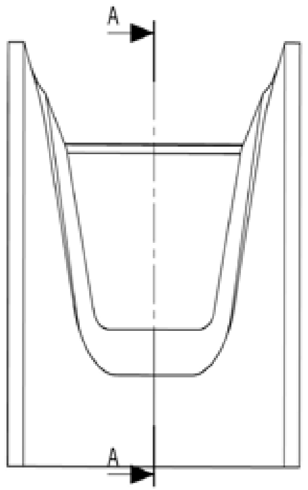
"The Be.e has a monocoque body; a unique construction in which the object's external skin supports the load, similar to an eggshell, eliminating the need for a frame and the usual numerous plastic panels.

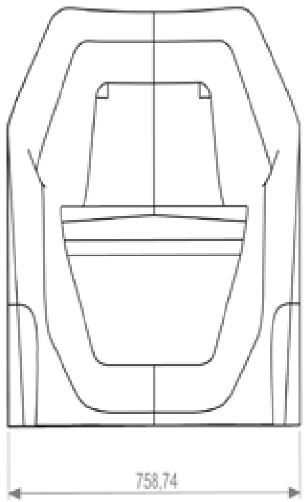
This structural engineering feat is made from flax and bio-resin, extremely sustainable, lightweight and strong".

Maarten Heijltjes & Simon Akkaya

Waarmakers Studio



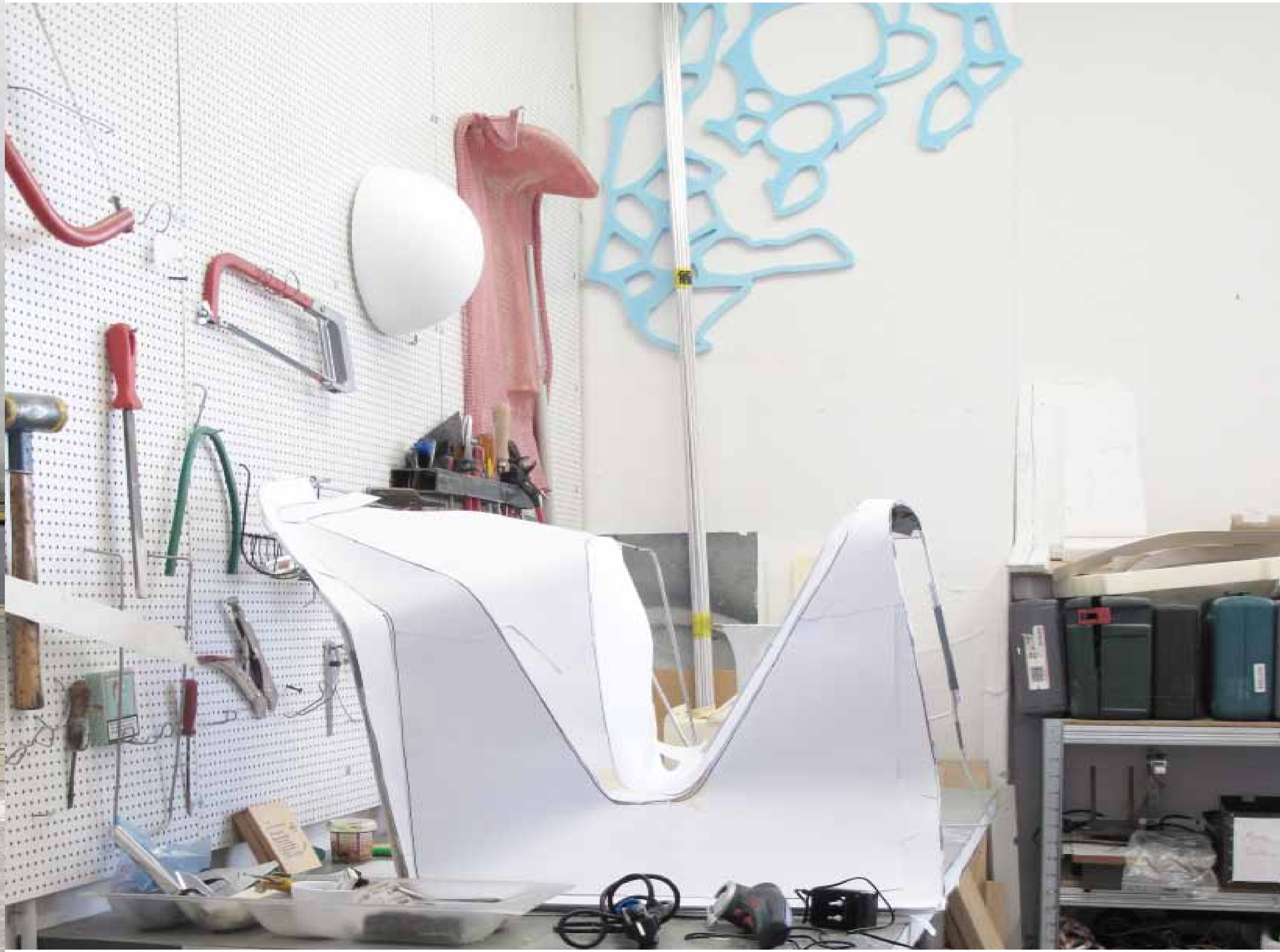




Hemp Chair

Flax & Kenaf fiber combined with
Water based thermoset Resin

Designed by: Wener Aisselinger



Hemp Chair

Flax & Kenaf Fiber combined with
Water based thermoset resin

Designed by: Wener Aisselinger

Natural Fiber Composite Paddles

Flax Fiber and Thermoset Resin

Designed by: Stu Morries

Natural Fiber Composite Paddles

Flax fiber and thermoset resin

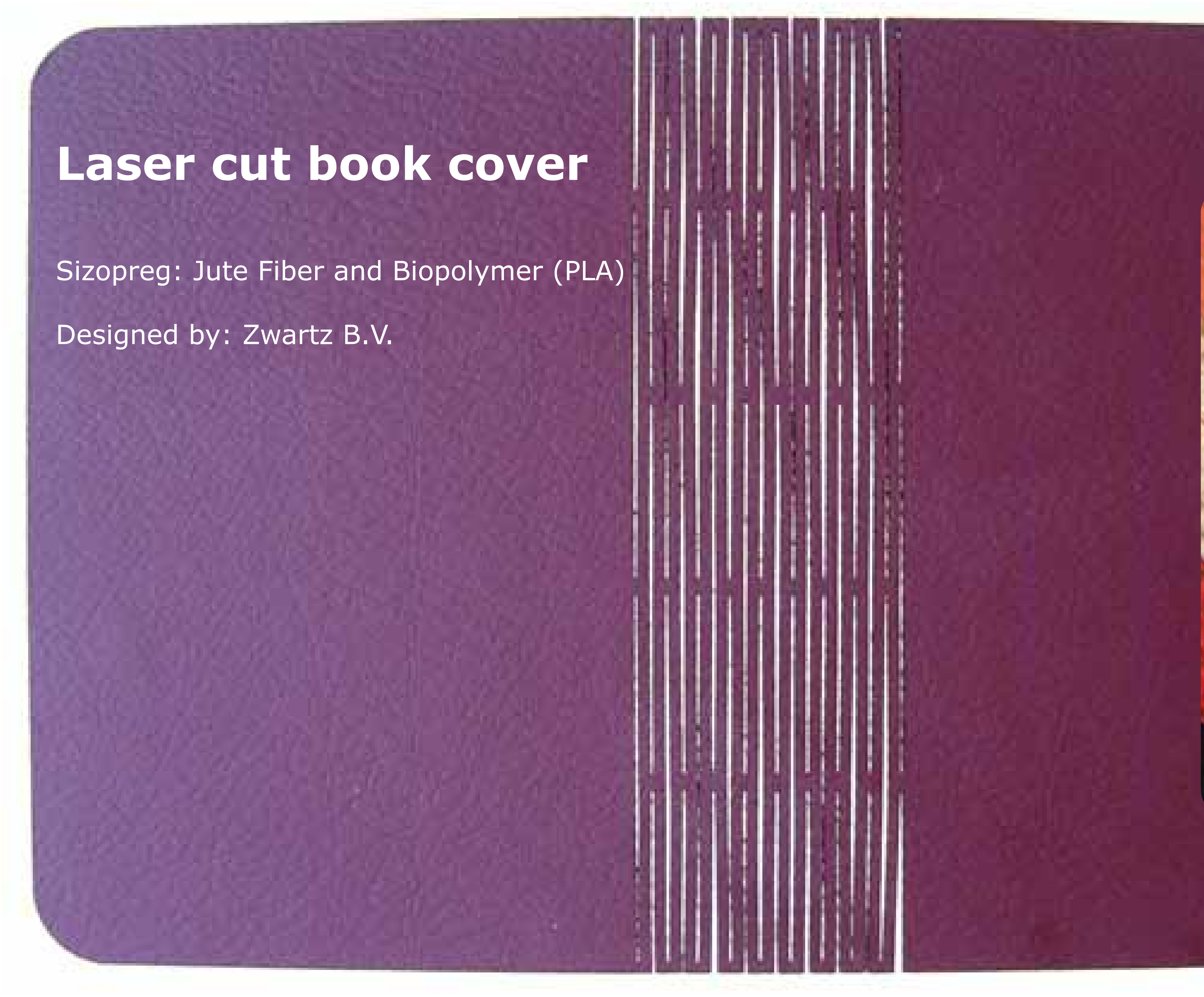
"On apparently the last sunny day of 2013, I took to the Bodensee in a sea kayak to give the paddles their maiden voyage.
First impressions are really positive: I was worried the paddle would seem flexible in comparison to a regular composite blade, but the paddle feels stiff and responsive, easily as stiff as a fibreglass, if not carbon, blade. Interestingly, the flax paddle is also slightly lighter than a standard fibreglass model. The blades also have a really unique and beautiful look. This 'natural' look and flax's eco-credentials will certainly appeal to a certain type of consumer."

Stu Morris and Mathew Morrisey

Laser cut book cover

Sizopreg: Jute Fiber and Biopolymer (PLA)

Designed by: Zwartz B.V.



CLARA Ukulele

Flax fiber combined with bioresin

"Clara is a concert ukulele designed to have the tone of vintage wood and the durability of cutting-edge, eco-friendly construction. Made from Ekoa - a proprietary, first-of-its-kind, renewable, biobased resin and flax composite. It provides a warm sound and feel with the toughness of carbon fiber. Clara's every detail is engineered to generate the acoustic quality of a much larger instrument. From its patented hollow-neck design to its high-tech eco-fabric and resin construction, the Clara is meticulously crafted by skilled artisans at Blackbird's San Francisco workshop, aided by CNC machining".

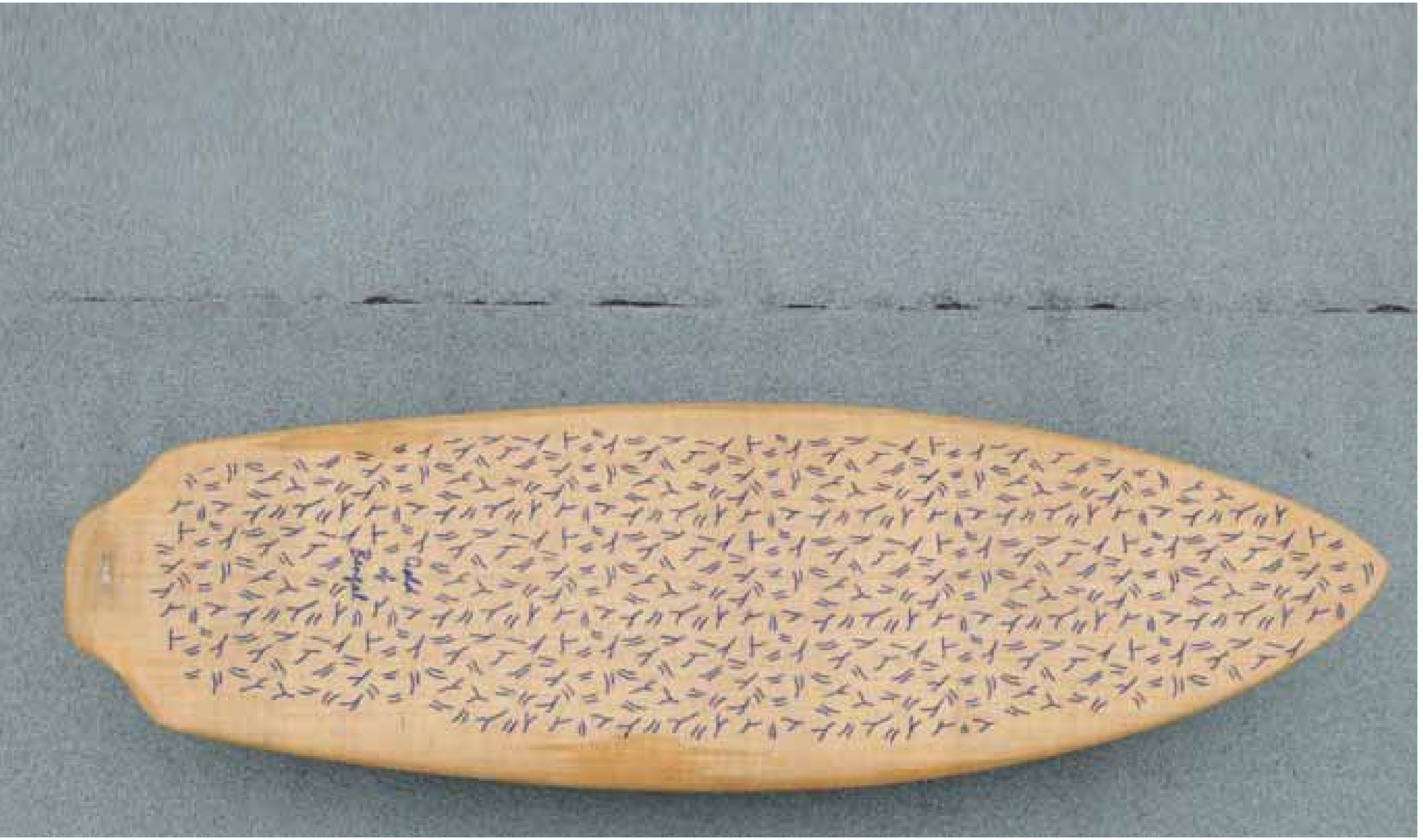
Designed by: Joe Luttwal
http://lingrove.com

CLARA Ukulele

Flax fiber combined with bioresin

“An authentic natural quality that adds an emotional layer to many applications”

Designed by: Joe Luttwal
http://lingrove.com



Designed by: Joran Briand
Splash surf board photographer: Cyrille Weiner

Splash surfboard

Jute Fiber combined with Epoxy Resin

Designed by: Joran Briand

The point with the board was to create a manifesto for the material. First of all, we want to show the mechanical qualities of jute fiber in a shaping context and second, experiment with embroidering. The surfboard is wide for an easy and multipurpose ride. Its average thickness allows an easy take of and the curving on this kind of soft typical waves of Bengal region. The embroidery is used as a reinforcement where the heels of the surfer hit the board during take off. The foam based on flour and baking powder. Close to bread recipe, this foam is light, stiff and ecologically friendly.

Designed by: Joran Briand
Splash surf board photographer: Cyrille Weiner

Toul Stool

Jute fiber combined with
Expoxy resin
Vacuum injected

Designed by:Joran Briand

“Cheap, clean and natural, its production uses very little energy and supports local agriculture.”

Designed by: Joran Briand
Splash surf board photographer: Cyrille Weiner

Tara Tari: Jute Sail Boat

40% jute fiber & 60% glass fiber
combined with epoxy resin vacuum injected

Designed by:
Corentin de Chatelperron & Ary Pauget

Corentin sailed 14.000 kilometers on board the Tara Tari made of composite to promote his vision of "simple living".

Beauty is in the eye of the beholder.

HEMP SUNGLASS

Hemp fiber and PLA

Designed by: Sam Whitten
Founder of Hemp Eyewear

FOCAL ARIA SPEAKERS

Flax fiber woven and preimpregnated fiberglass sandwich

Designed by: Focal JMLab

FOCAL ARIA SPEAKERS

Flax fiber woven and preimpregnated fiberglass sandwich

Designed by: Focal JMLab

COMPOS
CAFE CHAIR

Fully Biodegradable
Flax and PLA
Compression moulded

Designed by: Samuli Naamanka

”The goal of the three year long period of material research was to study the pressing of natural fibres for the demands of the furniture industry and achieve curves that are bent into three directions as well as to explore different thicknesses of the material. From the beginning it was clear, that we didn’t want any inorganic materials to be used. In the COMPOS chair the goal has been achieved. One of the significant benefits in comparison to plastic seats is the temperature of the surface, being much warmer and as a consequence more pleasant to sit on.”

COMPOS
LOBBY & BAR CHAIR

Fully Biodegradable
Flax and PLA compression molded

Designed by: Samuli Naamanka

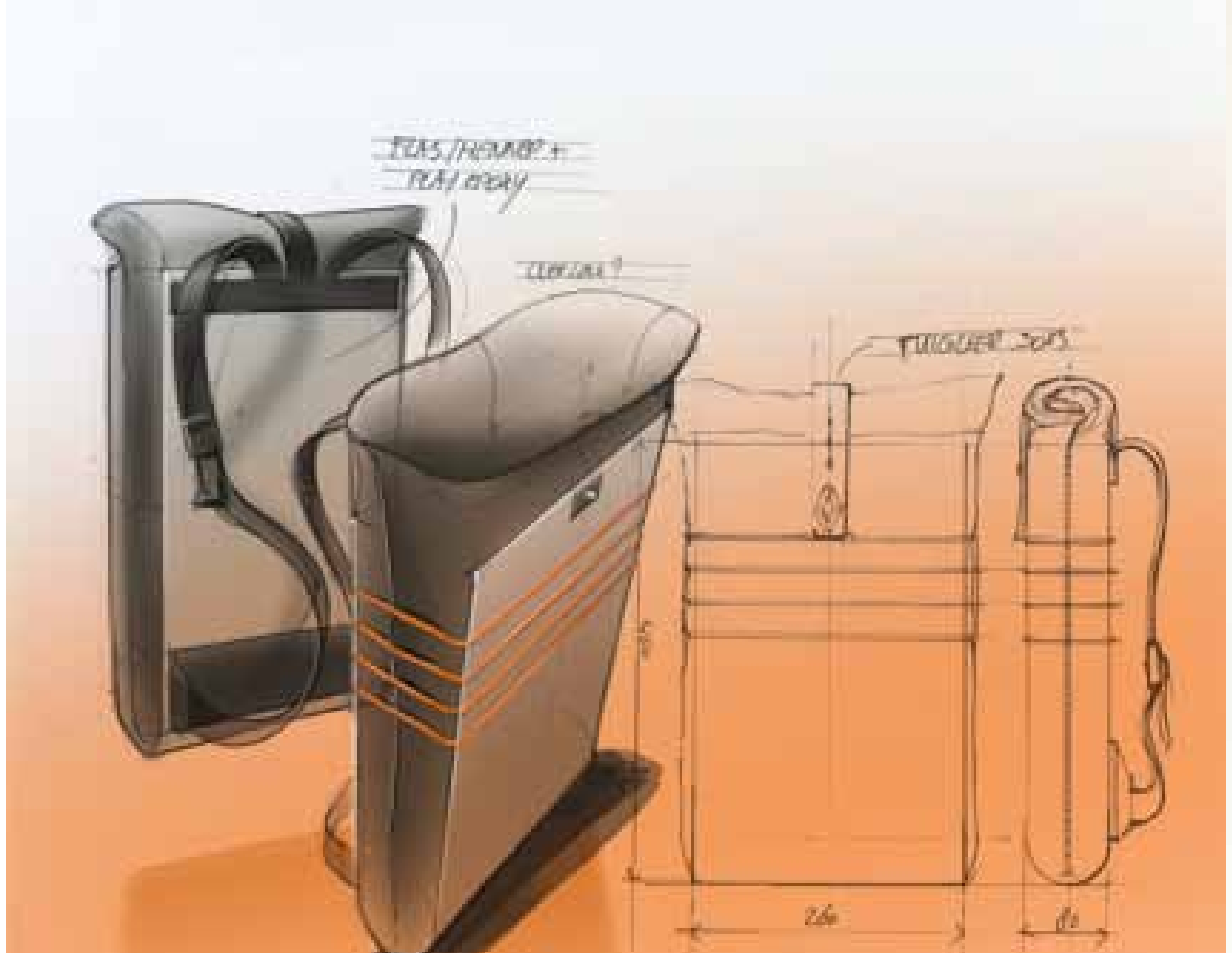
Ford Motor Company

Various interior parts made of biocomposites

Layered Chair

Coir fiber and natural latex

Designed by: Jorrit Takema



Flax fiber composite bag

Flax and Epoxy resin

Designed by: Jorrit Takema

Flaxland Kayak

Flax Fiber combined with Flax seed oil based resin

Designed by: Simon Cooper

"Our flax craft not only have high ecological credentials, they are aesthetically pleasing, lightweight and track well. Just like boats of previous generations, they harmonise with nature appealing to environmentally conscious boaters.

The combination of crafts involved in building gives the owner a sense of achievement and satisfaction resulting in a boat which, given care and respect, will last many years.

The canoes are ideally suited to inland waterways, rivers and lakes.
The light weight of our flax canoes makes them suited to portage and car topping or even towing with a bicycle."

Simon Cooper

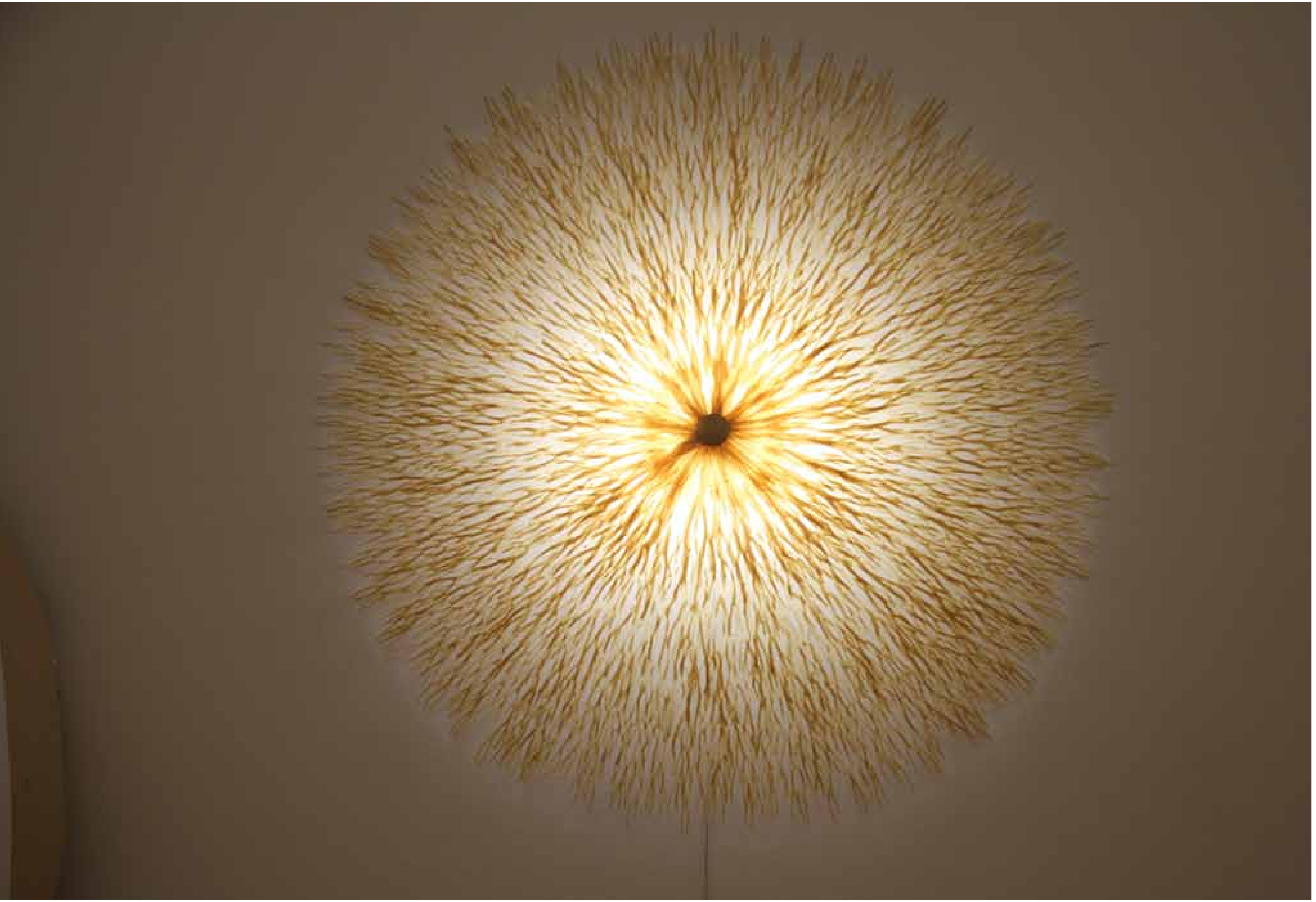
Rondeel Egg Packaging

Coir (coconut) fiber and natural latex rubber
100% biodegradable

Designed by: ENKEV B.V.

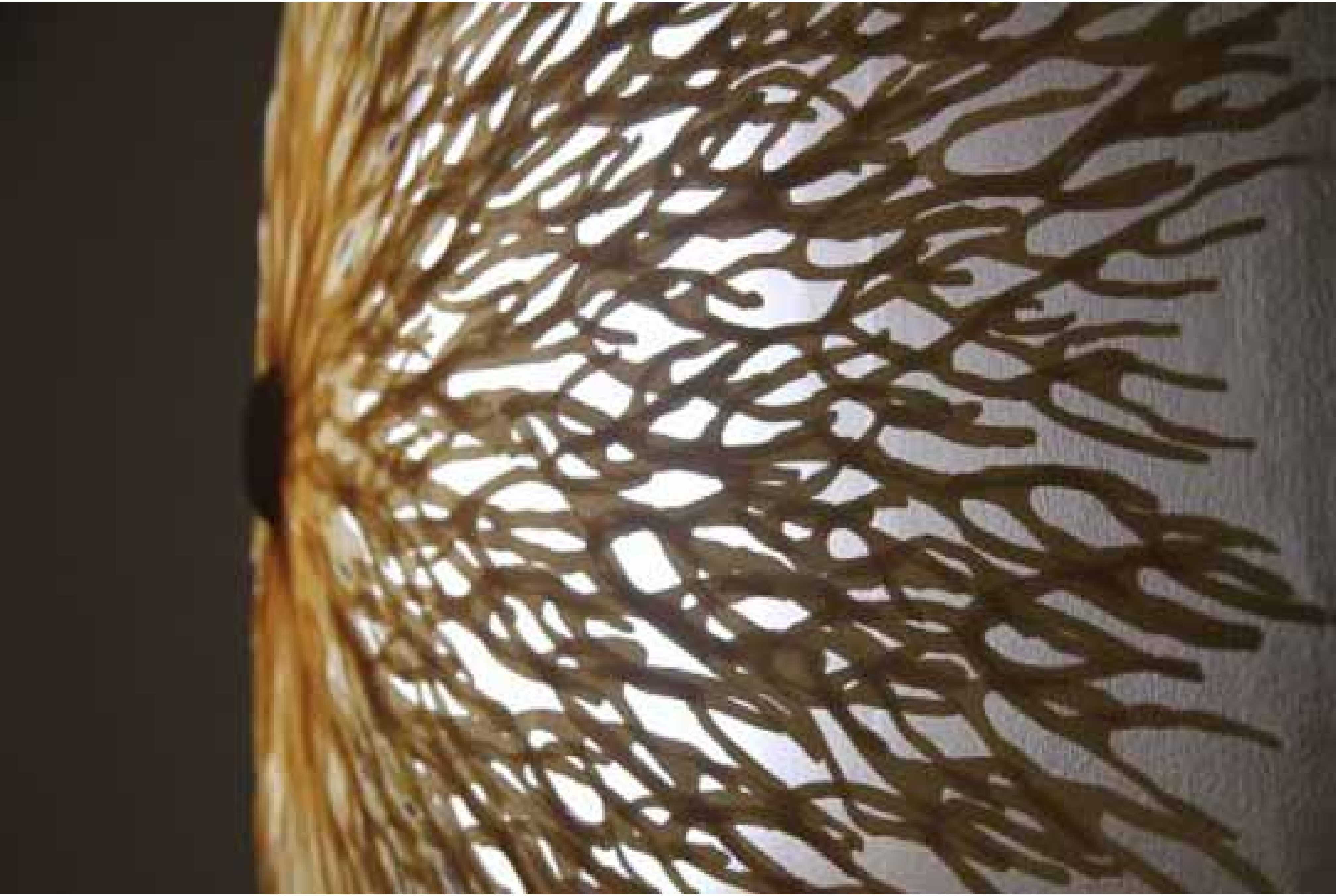
"Packaging as a medium to communicate sustainability and product brand"

www.enkev.com



My dream can not be taken by you.

Maori saying

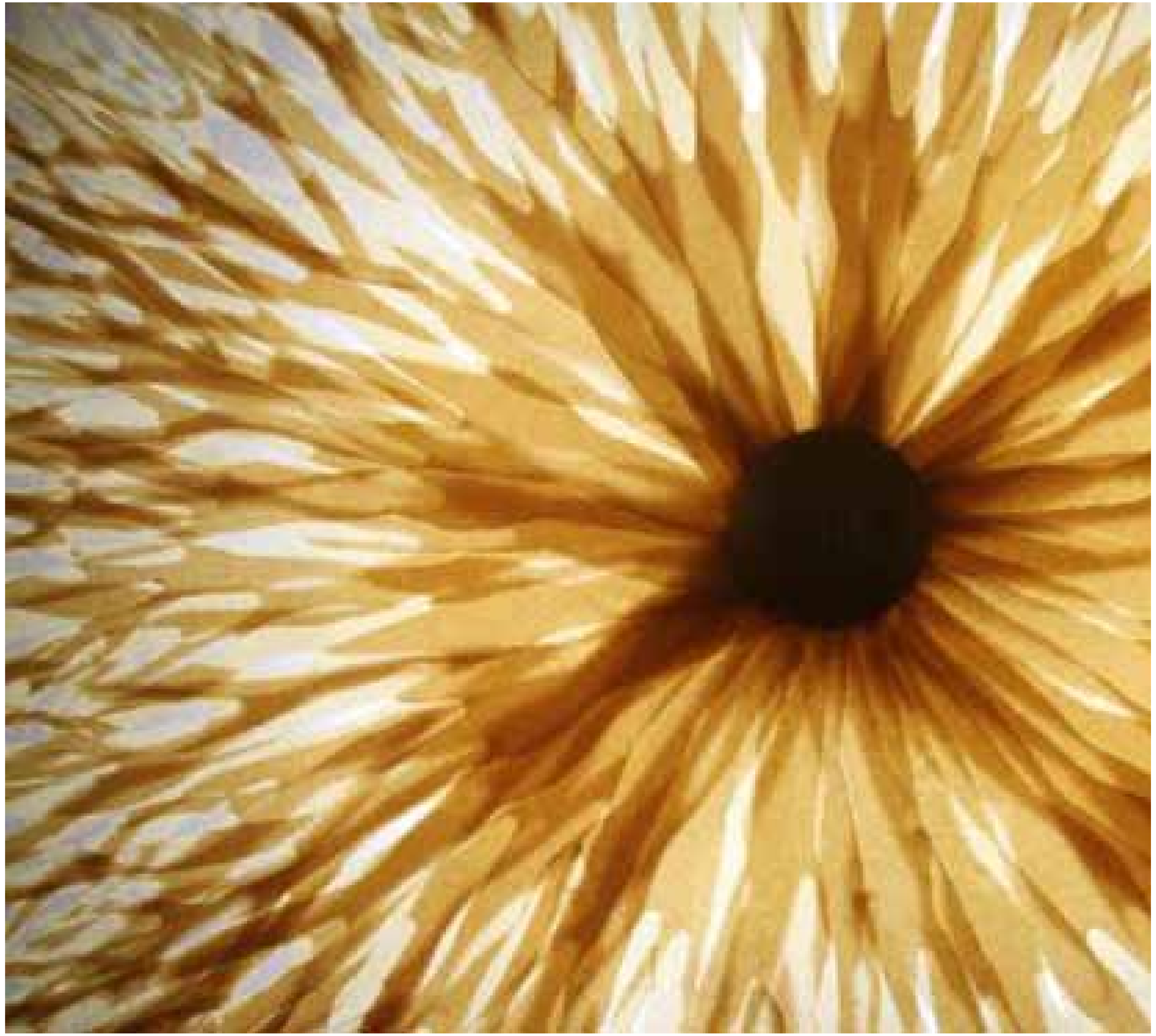


TIPU Lamp

Harekeke Fiber (so called New Zealand Flax) and PLA Biopolymer

Designed by: David Trubridge

"we are expressing our spreading awareness of, and connection to, Nature."



U nuhia te rito o te harakeke
kei hea te kõmako e kõ?

Take away the heart of the
flax bush and where will the
kõmako sing?

Maori Proverb

Surfboard

Harekeke fiber (New Zealand flax) and PLA Biopolymers

Designed by: Biopolymer Network, New Zealand

Cases for musical instruments

Biocomposites compression moulded
kenaf, flax and hemp fiber with PLA or PP

Designed by: Jakob Winter GmbH

"Based on their versatility natural fiber composites can be used for the production of an endless variety of products. In particular, products made from conventional plastics or wood can usually be replaced by natural fiber composites.
The benefit in comparison to solid wood products is the molding ability, high resistance to humidity and the associated weather resistance of the material. Compared to pure plastic materials natural fiber reinforced plastics can be attractive due to their natural look, low specific weight and the combined mechanical properties of wood fibers and plastics."

DELSEY BRIEFCASE

Flax fiber with thermoset resin

Designed by: DELSEY

Lightness Table

Jute and flax fiber combined with PLA

Designed by: David Derksen

www.davidderksen.nl

Lightness Table

Jute and flax fiber combined with PLA

Designed by: David Derksen

"This lightweight trestle table for working environments is designed according to the Cradle to Cradle principles. Based on a very innovative use of natural materials, a composite tabletop has been developed that consists of jute and linen textiles and bio-plastic. The table top made of biodegradable fabrics and plastics is completely compostable. The materials used give a warm and human touch. The lightweight table top is supported by a pair of stackable, anodized aluminum trestles."

David Derksen

www.davidderksen.nl

Guitar by Made

Hemp fiber compressed in lignin

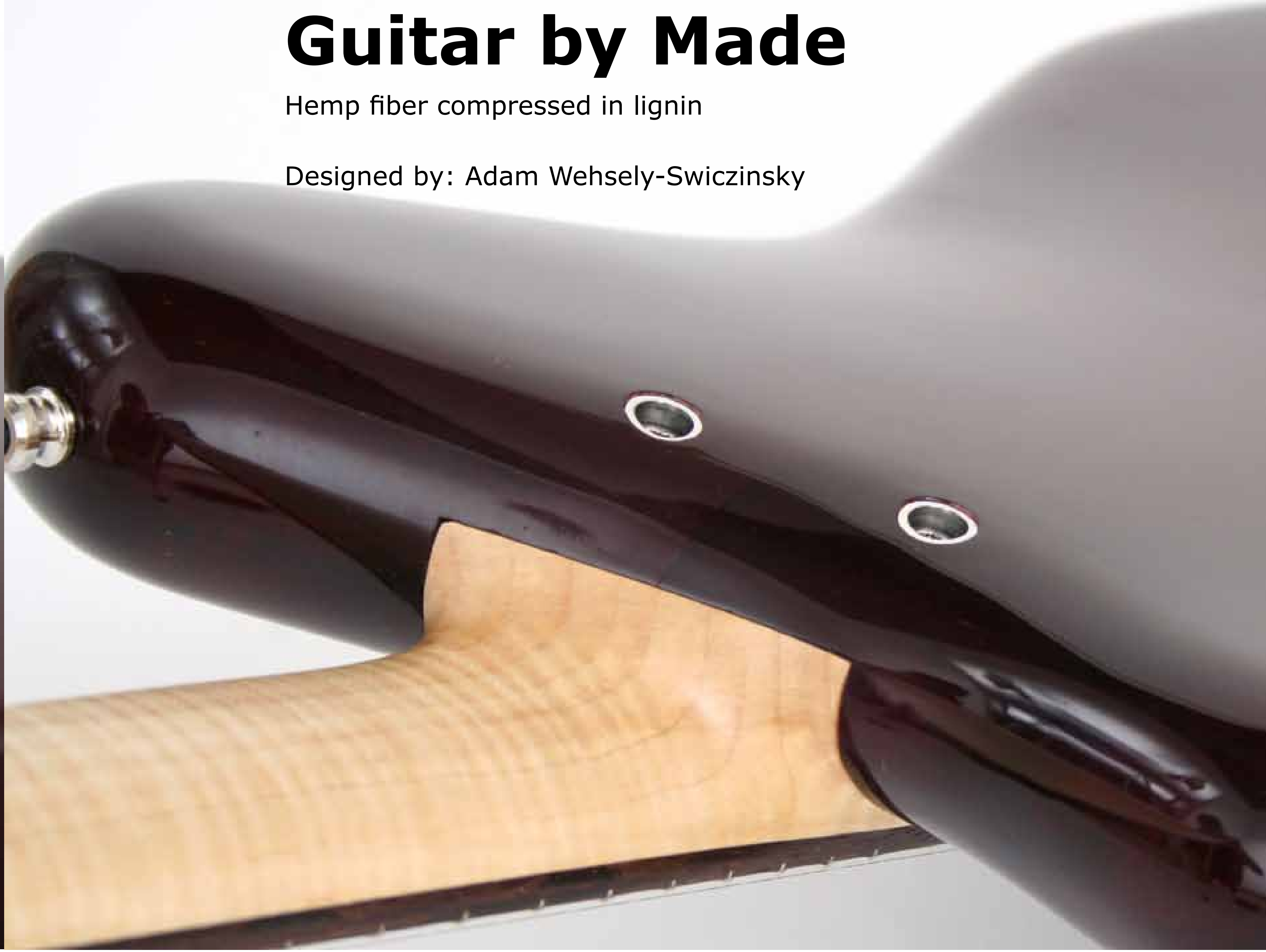
Designed by: Adam Wehsely-Swiczinsky

"I wanted to create an erotic object, the Venus of guitars, to support the special relationship between the musician and his/her instrument."

Guitar by Made

Hemp fiber compressed in lignin

Designed by: Adam Wehsely-Swiczinsky



Children’s mobility

Biocomposites

Designed by: Project at Burg Giebichenstein University for Art and Design

Low Chair by Pastoe

Hemp & Sisal fiber combined with polyester resin
Close mould vacuum injection by NPSP

Designed by: Maarten van Severen and Fabian Schwaerzler

Magdalena Abakanowicz

Jute burlap/fabric & resin
Seated and Dancing Figures (1974-1979)

www.abakanowicz.art.pl (Accessed 23 March 2015)

About meaning of sculpture

Art needs somebody to listen to its message, somebody to desire it, somebody to drink it, to use it like wine - otherwise it makes no sense.

What is sculpture? With impressive continuity it testifies to man's evolving sense of reality, and fulfils the necessity to express what cannot be verbalized.

Banished from Paradise, man found himself confronted by the space of the world. It was a territory unknown and inconceivable as inconceivable as are overabundance or emptiness. He tried to reach unknown powers, raising stones, building areas of special meaning…

With the development of society, sculpture began to visualize gods, to glorify leaders, to commemorate history, finally to decorate life. Today, we are confronted with the inconceivable world we ourselves created. Its reality is reflected in art.

From time to time a civilization falls into disgrace and art is destroyed by fanaticism and wars. This happens also today. However some monuments remain along the path, which for hundreds of centuries would be otherwise unmarked. Without these milestones of his spiritual odyssey man would be lost in darkness.

From the statement delivered by Magdalena Abakanowicz during the ceremony of conferring her the Award of International Sculpture Center for the Life Achievements. New York 2005.10.20

www.abakanowicz.art.pl/about/statement.php
Accessed 2015 March 23

Through these provocative images, the artist expresses the physical and spiritual condition of mankind.
As she says, they are "*about existence in general*."

Androgyn III (1985)
Jute burlap, resin, wood, nails, and string
www.metmuseum.org

Natural Fiber Composite Longboard

Flax fiber with epoxy resin vacuum injection

Designed by: René Roman Smeets

Driving the progress of Natural Fiber Composites

is exactly what the reputed automotive company Mercedes-Benz has been doing for many decades now. They have used natural fiber composites in many interior parts. Even used NFC, based on abaca fiber, in one exterior part. Mercedes-Benz used 46 kg of renewable materials in 87 components of the S-class (2013). NFC is also used in the A-class, C-class and the E-class.

Source: Mercedes-Benz

Biocomposite outdoor furniture

Designed by: Studio Ineke Hans
Photograph: Koos Schaart
Composite material: Nabasco by NPSP

"The N34 finds its origin in an old trade road to the north of Holland: via Coevorden to Zuid Laren, The Netherlands.

In old times starting villages or remarkable spots became resting spot for travellers and horses to find refreshments. Often these baiting places ended up with beautiful names like: the green pheasant, the black ox, the white elephant, the red dear, the golden lion....

Recently the N34 road in the Dutch province Drenthe got some prestigious artworks on these spots and we were asked to mark and link these works by renown dutch artists. We designed elements that all have the same base, but turn into milestones, information poles and seats where needed.

The areas also serve as baiting places for travellers to rest and refresh.

The single seats become a bench or picnic table depending on how they are positioned. The seat, table surfaces and other base tops are made of NABASCO: a new high impact nature based composite strengthened by natural fibres like flax and hemp. These materials more or less 'belong' to the Province Drenthe and fit to the 'green heart' this province likes to affiliate itself with."

Studio Ineke Hans

In the early days of recorded music (1877-1889) materials such as shellac, celluloid and hard rubber in combination with minerals and fibers were used for gramophone disc production. Sometimes the polymer was strengthened by the addition of natural fibers or even wood flour. Eventually vinyl records became common.

The natural polymer shellac was already in use for centuries in Asia for the production of artifacts. Sometimes shellac was combined with natural fibers to form a biocomposite material.

Gramophone discs

Some early gramophone discs were made of biocomposites

... there is still music in Natural Fiber Composites!

05

MAKING IT BETTER: NATURAL FIBERS

“Someday you and I will see the day when auto bodies will be grown down on the farm.”

Henry Ford

NATURAL FIBERS

The immense beauty of nature is in its workings. Nature produces high performance materials under "normal ambient conditions" of temperature and pressure. When the job is done all elements return to where they came from and the cycle repeats - This is truly amazing. This chapter is about natural fibers of plant origins. Plant cells play a crucial role in this. There are hundreds of plant fibers. But in the context of Natural Fiber Composites (NFC) only a selected group of natural fibers, namely Abaca, Coir (coconut), Flax, Hemp, Kenaf ans Sisal, will be discussed. These natural fibers are mentioned because they are already produced on an industrial scale and are available in very large quantities, not only for use in composites but for many other applications.

This chapter is not about biology or bio-chemistry of fibers. This chapter is only intended to introduce some key aspects of natural plant fibers so that the product designer could develop a critical understanding and hopefully contribute to considering using these materials in product design. For simplicity a few perspectives are taken in describing natural fibers in the context of NFC. One is considering the fibers from their botanical and biochemical perspective. This is becoming increasingly becoming important in the field of Nano-Technologies as chemists, biologists and engineers try to disaggregate plant fibers to get to the molecular levels. In the case of plant fibers it is often about the cellulose crystals. This is the micro level perspective. The macro side is extraction of the fiber from the plant materials and processing the fibers into semi-products, like preforms for composites. There is also a commercial perspective in which different interest groups try to position their material in such a way as to make a "green claim". For example the conventional viscose processing, with lots of chemical and energy use, to produce so called "bamboo fibers" and marketed as bamboo socks, T-shirts, underwear etc. These are man-made fibers but with cellulose of bamboo origins. However it can raise a more philosophical question about to what degree human intervention is permitted for a material still to be called "natural" instead of man-made. Because fiber extraction from plant material to be spun into yarn to produce textile can also be called "man-made". The distinction could be more normative than technical. Ultimately it is classifications and nomenclature that is arrived by consensus that qualifies materials to be in one category or another.

One of the objectives of this chapter is to introduce the product designer to natural fibers in a way that they could question and be critical about information that is presented to them in popular media and even in academic literature. Also to appreciate the diversity, the complexity and the beauty of natural fibers. Hopefully this appreciation could trigger product designers, be it from an industrial product design school or arts and crafts school of thinking, to rediscover the beauty nature has to offer and to use these wonderful materials, as far as possible, in their "natural state".

Why only a selection of natural fibers: The availability on industrial scale.

Most if not all plants have some sort of fiber. Fibers are present in plants to provide support, defence and to fulfil storage functions. Often the supportive characteristics of plant fibers e.g. strength and stiffness, are of interest for composite application. In other applications the defensive characteristics, namely due to the polymer lignin, that is present to protect the cellulose in the fibers, could be of interest for example when slower bio-degradation of the fibers is a functional requirement of the product concerned.

In the context of Bio-Based economic development there are efforts being made to utilize "agro wastes" for fiber extraction and possible use in composites. There are several "under exploited" and "underutilized" natural fibers available for a wide range of applications. However the supply chains of these fibers are not fully developed therefore availability in the right requirements and quantities poses problems. Therefore the fibers discussed in this publication are a selection of natural fibers that are produced on an industrial scale so that supply chain issues are not a constraint for the use in composites. The most commonly used natural fibers in (industrial) application such as NFC are abaca, coir (coconut), flax, hemp, jute, kenaf and sisal fiber. At present most of the large scale composite applications are based on some of these fibers. But fibers such as curava, cotton, pineapple leaf, rice husk, ramie, several sorts of grass could also be used in composites.

What is a natural fiber?

It may seem astonishing that one of the worlds abundant materials, natural fiber, is not defined in an internationally harmonized way. There are many notions of what a fiber is. This depends on the discipline that discusses fibers. For example, is a strand of wood or wood flour, a natural fiber? Are bamboo particles natural fiber? So the lack of definition could cause problems both commercially and technically. It is not the intention to resolve this sensitive issue here. It may be sensible to realise that not every part of a plant is a fiber nor every plant based material is a natural fiber. So regenerated cellulose i.e. viscose is not a "bamboo fiber". Though it is possible to extract bamboo fibers, at present the production is very limited.

Generally and for practical purposes a natural plant fiber could be the fibrous material of short carbon cycle origin, with a substantial length to diameter ratio, and in its natural form it could be spun.

Generally in NFC fibers are not used in the form they are extracted from the crop. From a NFC perspective it makes little sense to consider the mechanical properties of the fibers in their extracted state. Natural fibers are processed into semi-finished products such as cut fibers, low twist yarns, woven & non-woven mats etc..
As there are many possibilities to configure the natural fibers into semi-finished products as input for composites, it is virtually impossible to provide data for the different pre-forms. However, for the curious reader some physical and chemical properties of natural fibers are provided. There are several publications showing different data of properties. Therefore Table 5.1 provides a general impression of the biochemical composition and Table 5.2. provides very basic physical properties of some fibers used in NFC. The variation in data could be due to methods of measurements, country and type of origin, section and the time at which the crops were used for fiber extraction. In addition there are several commercial standards of fibers which could include physical parameters as well. Therefore data presented is indicative only and intended to provide the reader some idea about the fibers. However due to the very large volumes of natural fibers produced, the variations can be managed for technical applications.

Table 5.1: A general impression of the bio-chemical composition of selected natural fibers

Only key components are mentioned. There is variability of properties caused by many factors hence data is indicative only.
Percentages are weight based. Some data not adding to 100%.

Fiber	Plant part	Cellulose %	Hemi-Cellulose %	Lignin %	Pectin %	Fat/ Wax/ Ash/ Water solubles %
Abaca	Leaf (Pseudo stem)	63-70	20	5-6	< 1,0	2,0
Coir (coconut)	Husk Nut cover	36-43	< 1,0	41-45	3-4	< 2,0
Flax	Stem bast	64-67	17-18	2-3	2,0	9-12
Hemp	Stem bast	67	16-17	3-4	1,0	2-3
Jute	Stem bast	60-65	21-24	12-14	2,0	2-3
Kenaf	Stem bast	60-70	20	18	< 1,0	< 1,0
Sisal	Leaf	66-70	12-13	10	1-2	2,0

Table 4.2: Dimensions of selected plant fibers

Fiber bundles, Ultimate Fiber Cell, length etc. (Indicative only)

Fiber	Range of Length mm	Range of Diameter mm	Range of Cell length mm	Range of cell diameter µmm	Shape
Abaca - Normal Abaca - Tow	1000 - > 2000 < 600	0,01- 0,28	3 - 12	6 - 46	Round / Oval
Coir - Long Coir - Short	120 - 300 30 - 120	0,10 - 45	0,30 – 1,0	12- 24	Round / Oval
Flax - Long Flax - Short	200 - 1400 < 200	0,04 – 0,62	4 - 77	5 - 76	Polygonal
Hemp - Long Hemp - Short	1000 - 3000 < 1000?	0,03 – 0,50	5 - 55	10 - 50	Polygonal
Jute	150- 3600	0,03 – 0,14	0,80 – 6,0	15-25	Polygonal / Oval
Kenaf			1,5 – 11,0	12 - 36	Cylindrical
Sisal - Long Sisal - Short	600 – > 1000 < 600?	0,01 – 0,46	0,8 – 8,0	7 - 47	Cylindrical

The sources of natural fiber

Natural fibers could be of animal, plant or mineral origins (for example asbestos).
Most of the current applications and Research & Development related to composite applications were focused on natural fibers based on plants. However there is exploratory research into the use of non-plant based fibers such as silk, chicken feathers etc. in composites. The focus of this publication is on natural fibers of plant origin.

The fibers in different parts of the plant perform specific functions. For example the fibers in the coconut husk protect the seed (coconut) and increase its chance of survival. The high lignin content protects the coconut husk from rapid biodegradation. The fibers in the bast of the flax stem provide strength and flexibility so that the plant as a whole is protected so that the plants seeds come to maturity and ensure the continuity of the species. In the case of sisal plants the fibers in the leafs provide support so that it can fulfil its function of photo-synthesis and bring forth young shoots to ensure its continuity. It is all about survival and continuity of the species. In a similar manner the use of natural fibers, that are renewable, can also contribute towards the well-being and continuity of human beings.

Plant Cell structure and organization

The study of plant cell was and is the domain of botanists and biologists. However the increasing involvement of engineers and chemists in this domain is increasing our understanding of plant cell structure, organization and even the biochemical processes of plant cells. The objective here is to provide a basic and a “popular” description of the structure and organization of natural fibers from a bio-chemical perspective. This may enable the product designer to engage in the dialog and ask the question:
“What is exactly meant by “natural fiber” as used in composites?”
Especially today when scientists often talk about nano-technology, nano fibers for composites and cellulose nano-crystals etc.

Literature on NFC often mentions properties of different natural fibers. But very few mention how these properties were measured or what exactly is being subjected to the measurement. This publication also went down that path - for convenience sake! Therefore the tables provided should only be considered as indicative. Efforts to harmonize the measurement and provide uniform sets of data is still to come. But in recent years these shortcomings have been recognized and efforts are being made to provide clarity and precision.

Nature creates these amazing structures in plants with minimal energy and every substance and structure has a specific function. Nature has been perfecting these materials over millions of years. Therefore intervention by man in these processes means additional use of energy. It is recognized that fiber extraction also needs energy. But more and more energy and other substances will be needed when efforts are made to decompose, deconstruct and undo natures working. The concept of Bio-Refinery is an attempt to maximize and preferably optimize the utility of bio-resources. But if human intervention is more effective and efficient needs to be seen. The point being made is that it could be more energy efficient to use materials as close as possible to the natural form. For example use natural fibers with minimal processing. Deconstructing the material to the “nano-level” means it could be inefficient and also the meaning of the material is lost or changed.

The hierarchical structure of the plant cell wall

Plants can transform inorganic carbon dioxide (CO_2) to organic compounds. Plants cannot move about for sunlight and water hence have to deal with their development in the place where they are rooted. This is simply a natural process. The plant development is a complex bio-machinery at work and this subject is beyond the scope of this book.

Before proceeding further, a brief explanation is provided about the key bio-chemical components of plant fibers.
Cellulose is the most abundant natural biopolymer on this planet. All natural plant fibers contain cellulose.
The cellulose is embedded in extracellular matrix, consisting of lignin and hemi-cellulose.
Lignin is the second most abundant biopolymer in the world followed by hemicellulose. Lignin accounts for some 30% of the organic carbon on earth. Taking these substances into account natural fibers are called Lignocellulosic fibers.

In fiber cells cellulose is created by linear chains of β-D glucose. These glucose chains by various bonding mechanisms and crystallization form cellulose microfibrils. These cellulose crystals and microfibrils exhibit very high mechanical properties hence are of interest in nano-technology, for example. There are different polymorphs of cellulose, such as cellulose I, cellulose II, cellulose III and cellulose VI.

Lignins are natural binders. There are many type of lignins. It is claimed to be one the most complex but fascinating substances of the plant world. Because lignin is hydrophobic (water repellent), biodegrades gradually and provides mechanical rigidity to plants, it forces them to grow skywards. Lignin protects the plant against pests, mechanical wounding and pathogens. But lignin coated cells, such as the xylem vasculature (sort of a tube) can transfer water from the root to the plants leaves. Pectin also plays an important role in holding different parts of the fiber architecture in place. Other compounds include tannins, waxes, fats, extractives, inorganic matter etc.. Each component performing a specific function in the development and survival of the plant. Natural fibers are biocomposites themselves; designed by nature maybe 3.500.000 years ago or even longer.

The bio-chemical composition of natural fibers could pose challenges when combined with man-made polymer matrix. This is a matter of compatibility between natural fibers and the synthetic polymer matrix. The inter-face domain between natural fibers and polymer matrix to maximize the bonding has been thoroughly researched and solutions are proposed. It should be noted that nature has resolved the so called interface issues in an elegant way.

Elementary cellulose microfibrils (3nm) can aggregate to form larger microfibrils.
In the primary cell layer the microfibers could be 5-10nm and in the secondary layer 30-50nm.
The Degree of Polymerization (DP) refers to the microfibril length. DP of cellulose in the primary wall could be a few hundred to thousands, while in the secondary cell wall it can be as long as 15.000 glucose units. How all this is regulated is unknown but the DP varies from plant to plant. The DP, cellulose content in relation to other cell wall polymers, the microfibril angles in the secondary walls are all tightly regulated mechanisms of nature. For the present purpose it is assumed that there is a process of cellulose synthesis in plant cells resulting in cellulose microfibrils being deposited on the cell walls and results in specific properties of that plant.

Fiber structure: Jute fiber as an example

The jute fiber will be used to describe the structure of lignocellulosic fibers. Other fibers like abaca, coir, hemp, flax, kenaf, sisal etc. could have similar general tendencies but the composition and characteristics will be different. The explanation would provide an idea about the hierarchical structure and organization of plant fibers in general.

Jute (belongs to genus Corchorus of the order Tiliaceae) plants yield a bast (Phloem) fiber.
Of the thirty different types only *C. Capsularis* (commonly known as White Jute) and *C. Oilitorius* (commonly known as Tossa Jute) are used for commercial fiber production.

Jute is an annual plant and can reach a height between 2,5 to 3,5 m and a basal stem diameter of about 25 mm. The stem of the jute plant is a hollow woody core, covered by a layer or bast. This bast contains the long jute fibers. The fibers and other tissues that constitute the bast are separated from the woody stem by a process called retting. Retting takes about 2 to 3 weeks in water. When the retting process is considered to be completed bundles of fibers (called reed) are separated from the woody core ready for further processing. The reed could be 1,5 to 4,5 metres long and show a mesh like structure as shown in figure 5.1. Only about 5-6% of the plant is jute fiber. But in jute producing countries the woody core is used for various applications as well. Nothing is wasted. The reed bundle consists of about 15 to 30 fiber cells. And each fiber element will consist of about 5-15 cells, called ultimate cells. The number of ultimate cells would vary along the length of the jute fiber element. The ultimate cell could be 2,5-3,0 mm long on average and 18-20μm in the middle. The ultimate cells are not cylindrical but tapered from tip to tip. The structure is shown in figure 5.1.

These structures are held together by various bonds and substances. Due to its structure jute is known as a multi-cellular fiber. Generally plant cell wall consists of a primary cell wall (P) and secondary cell walls (S). The secondary cell wall is further divided in to three layers, referred to as S1, S2 and S3. See figure 5.2. which shows a stylized section of the micro structure (morphology) of jute fiber.

Initially the primary cell wall is formed with randomly oriented microfibrils.
In the secondary cell wall the layer S2 occupies the largest volume and influences the properties of the cell. S2 layer has three hierarchical microstructures, known as macrofibril, microfibril and micelle. The secondary cell wall tends to be thicker and rigid in comparison to the primary cell wall. The composition and organization of the cell walls determines the evolutionary diversity of plants.

Figure 5.1.: Jute Stem and Fiber Structure

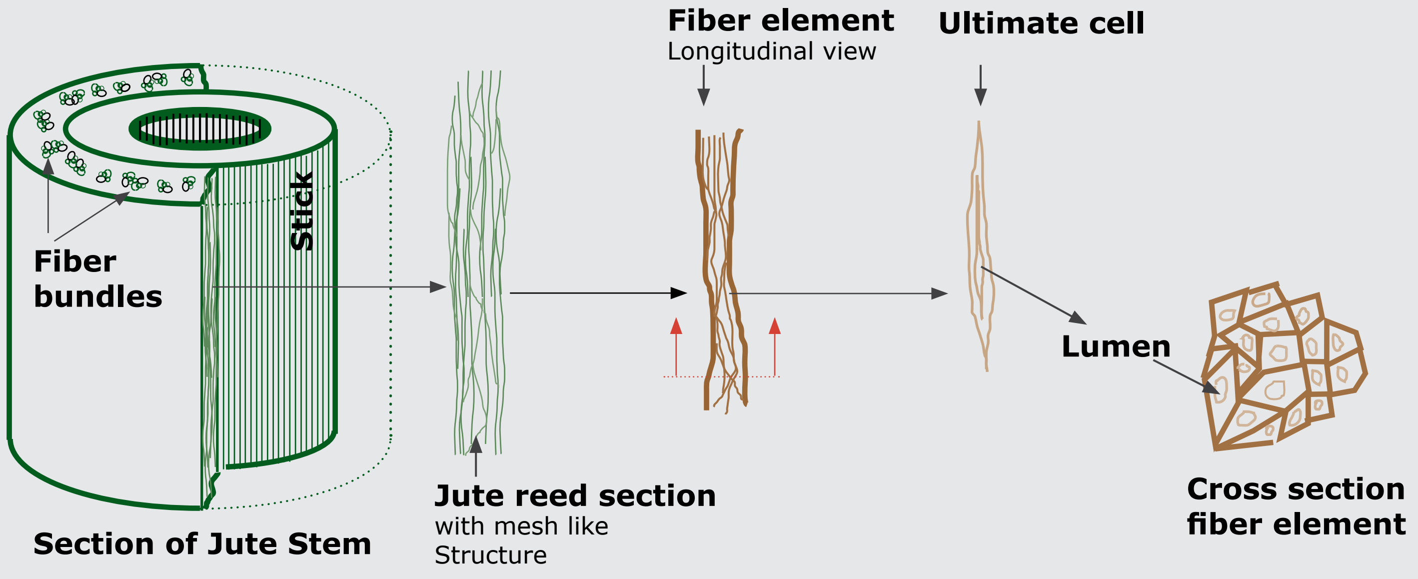
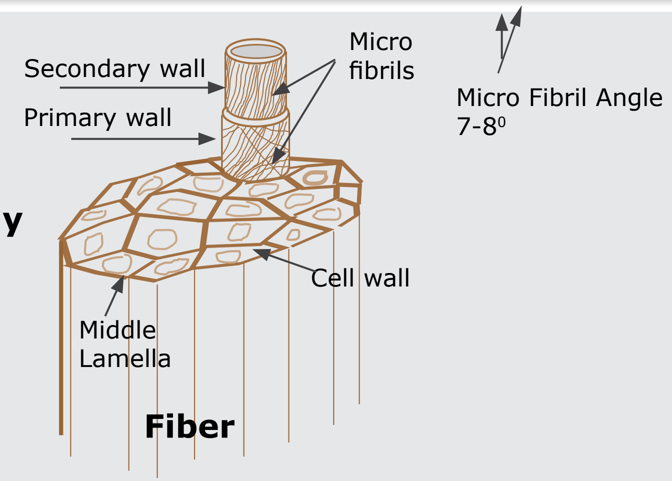


Figure 5.2.: Jute Fiber Morphology

Micro-structure



Source: D. Sur (2005) Understanding Jute yarn

The plant cell would have a lumen and middle lamella regions. The cell lumen is the area by which the cell is supplied with various substances triggering several biochemical processes. The substances that form the middle lamella can be different from plant to plant. In jute fiber cells the middle lamella mainly consists of lignin. There is less lignin in the primary and secondary cell walls of jute but they are rich in hemicellulose. In hemp fiber the middle lamella consists of lignin and pectin, while in flax the main part is pectin.

In the secondary cell walls the microfibrils are arranged in parallel and in spiral form. This orientation is called the Micro-Fibril-Angle (MFA). For jute this angle is about 7-8° in relation to the axis of the fiber. MFA will strongly influence the property of the fiber. Like jute fiber other bast fibers such as hemp and flax also have an MFA of less than 10°. These fibers exhibit higher resistance to axial tensile stress compared to fiber cells with MFA of say 30°. A lower MFA fiber could have a weak mechanical property such as elongation. Higher MFA could be very beneficial for impact resistance.

The key point for product design is that it is incorrect to conclude that one property automatically means one fiber type is better than another, a mistake often made. Product designers could try to appreciate that nature has created and fine tuned, over millions of years, different natural fibers, which themselves are biocomposites, with different characteristics for optimal performance. There is a very good reason why in one fiber type the MFA is less than 10° and another more than 20°. Therefore each material should optimally match the purpose of the products functional, technical and aesthetic requirements. These are lessons to be learned from nature.

The typical properties of fibers are mentioned but will not be discussed further in detail:

- √ Physical dimensions (fineness, length diameter, density)
- √ Strength and elongation
- √ Elastic nature
- √ Flexural and Tensional Rigidities
- √ Moisture Absorption and Swelling
- √ Thermal properties
- √ Electrical properties
- √ Optical properties
- √ Degradation function
- √ Frictional properties
- √ Colour and lustre (not of importance in composites)
- √ Effect of chemicals (e.g. acids, bleaching agents etc.)

BRIEF DESCRIPTION PLANT FIBERS:

Abaca, coir (coconut), flax, hemp, kenaf and sisal fiber

In the previous section jute fiber was briefly discussed. In the followings sections the plant fiber types abaca, coir (coconut), flax, hemp, kenaf and sisal fiber will be briefly described.
These natural fibers are presented as potential candidates for NFC mainly because these fibers are produced internationally, on industrial and large scale. This ensures the availability of these fibers for NFC applications.

International availability of selected natural plant fibers

Table 5.3 provides an estimate of world production of the fibers concerned.

Table 5.3:
World production of selected natural fibers
Source FAO (2012)

Fiber	Annual production
Abaca	99.700 tons
Coir (coconut)	1.057.700 tons
Flax	716.500 tons
Hemp	79.700 tons
Jute	2.953.000 tons
Kenaf & Jute like fibers	289.300 tons
Sisal	383.900 tons

The world production of abaca, coir (coconut), flax, hemp, kenaf and sisal is estimated at some 5 to 6 million tons per year. The global natural fiber composites use is estimated, optimistically, at some 150.000 tons per year. This excludes wood plastic composites. The international glass and carbon fiber based composites is estimated at some 8,7 million tons in 2012. So it is safe to suggest that the availability of natural fibers can not be a constraint for use in NFC applications. The figures mentioned are indicative only but even then the key message is that there is more than sufficient natural fiber available for composite applications.
Millions of rural farmers, in emerging and developing countries, are involved in growing the crops and extraction of the so called J.A.C.K.S. fibers (jute, abaca, coir (coconut), kenaf and sisal). While flax and hemp are grown in more economically developed countries like France, Belgium, Netherlands, Canada etc..

ABACA FIBER

Indigenous to the Philippines, abaca (*Musa Textilis Nee*) became known in some circles as Manila Hemp. This of course is a big mistake because hemp is a bast fiber, while abaca is known to belong to the leaf family of plant fibers. This mistaken name was propagated by the colonialist. The abaca plant looks similar to a banana plant. Like many crops of the tropics abaca too has a botanical economic history that could read like a thriller story. The same could be said of jute fiber. In addition to Philippines abaca fiber is produced on a commercial scale in Ecuador also. With more than 80% of the world supply, Philippines is by and large the dominant producer of abaca fiber internationally.
Harvesting abaca is very labour-intensive. Each stalk must be cut into strips which are then scraped (usually by hand) to remove the pulp. The long white fibers are then washed and dried, and baled for transport. Efforts are being made to mechanize the production of abaca fiber.

Abaca fiber is a strong natural fiber. It is used as raw material for cordage, fibercrafts and pulp for the production of speciality paper products like security & currency papers, teabags, cigarette papers, meat and sausage casings, non-woven and other thin printing papers. Speciality paper products account for about 80% and 14% of abaca produced is used for cordage products.

COIR (Coconut) FIBER

Coir fiber is one of the versatile products of the coconut palm (*Cocos Nucifera L.*), also known as the Tree of Life. Generally the coconut palm has a lifetime of about 70 years but could yield up to 100 years even. Under good growing conditions, year in year out, about 100 to 160 coconuts are produced by each palm. The palm also known as coconut tree is truly a source of renewable raw materials for both food and non-food products. This makes the coconut tree and the coconut unique. For non-food products the hard coconut shell and the outer coconut husk are used.

The coconut husk is processed to obtain coir fiber and coir pith, an excellent renewable growing medium for plants. Coir fiber is used for the production of a wide range of products. Typically it is used for the production of carpets & door mats, geotextiles, mattresses, automobile seats, packaging and a wide range of brushes, twines & yarns. The fibers can be extracted by various methods, starting with retting in water, typically between 21 – 90 days or by wetting/soaking in water from 1-3 days. After the husks are naturally softened in water, the fibers are extracted by hand-beating, decortication or de-fibering mechanisms. The fiber is then further cleaned by sieving before being used in further process steps, like yarn making or for the production of non-woven mats.

Compared to other natural fibers coir fibers have a high percentage of lignin. Therefore in applications where gradual bio-degradation is needed, coir fiber is the best candidate. The helical internal structure of this fiber and high micro-fibril angle of 35^0- 40^0 results in a high elongation characteristic that makes the fiber most suitable for applications where resilience and impact resistance are important design parameters.

The coconut tree grows in many countries of the world. The coir industry is only fully developed in a few countries like India and Sri Lanka. In recent years other countries like Vietnam and Philippines are increasing coir fiber production.

FLAX FIBER

Flax (*Linum uaitatissimum L.*) plant can grow to heights of 1200 mm but with a thin stem diameter of about 1,0 to 3,0 mm. It is an annual plant. Flax plants are grown for their seeds - Linseeds - or for the fiber. The timing of harvesting of linseeds and the stems for fiber extraction has to be optimized. The characteristics of the fibers extracted from "seed flax" and "fiber flax" differ. The seed flax fibers being shorter and coarser. Flax plants grow in many temperate and sub-tropical area of the world. Flax is produced European countries such as France, Belgium, Netherlands and some Baltic states. But also large volumes of flax is produced in Canada, Russia and India.

Flax can be harvested using different methods. Once the plant is harvested it can be dried for 10-15 days in a sort of semi retting. In this process of retting the stem and the fiber bundles are loosened and separated. Once the (dew) retting process is considered to be complete the stems are put through a multiple step process decortication to separate the woody part, known as shives, and the flax fibers. Consequently the flax fibers could be processed further to obtain long and short fibers. Only about 6-8% of the flax plant is recovered as flax fiber. In addition to mechanical and semi-biological processes, efforts are being made to extract fiber by enzymatic processes. However these processes are still not used in large scale industrial extraction of fibers.

Similar to other plant fibers flax has been used for hundreds of years for various applications. Linnen is the major value added use of flax fiber. Traditionally flax fiber has been used for rope and cordage manufactures. In recent years flax is increasingly being used in technical applications such as composites.

HEMP FIBER

Hemp (*Cannabis sativa L.*) plant can grow to heights of 1000 to 4000 mm. The stem diameter can be about 5,0 to 20,0 mm. It is an annual plant. It seems the hemp plant was originally cultivated in central Asia. But at present hemp is cultivated in temperate zones of the world. It has been grown in European countries such as France, Belgium, Italy, Spain, Hungary, Romania etc. It is also grown in Canada. Growing hemp is illegal in many countries, even though the plants used for fiber production are different to those for the production of narcotics.

After harvesting the hemp stems are retted, so that the stem tissues and the fiber bundles are loosened. The retted stems then undergo multi-step processing where both long and short hemp fiber are produced. In the process the woody parts (shives) are separated. The long hemp fibers are used for textile production. Hemp fiber is used for composite application.

KENAF & JUTE FIBER

Jute fiber has already been discussed in an earlier section of this chapter so will not be repeated here.

Kenaf (*Hibiscus cannabinus L.*), a bast fiber, is allied to the jute fiber and shows similar characteristics. Kenaf is a member of the genus Hibiscus in the family *Malvaceas*. Kenaf has many applications including the production of natural fiber composites. This fiber has the potential to be used in low density panels, pulp and paper.
The kenaf plant is an example of a number of woody-stemmed herbaceous dicotyledons grown in the tropics and subtropics. The fibers can be extracted from the bast of the stems or stalks. Kenaf is annually cultivated from its seeds for the fibers. The first step in processing is cutting of the kenaf stalk close to the ground which is then left to defoliate. Then the stalks are stripped in decorticating equipment, washed and dried in the sun.

Kenaf fiber is produced mainly in India and China, followed by Bangladesh. Malaysia is in the process of developing kenaf cultivation and processing. This is a government initiative to diversify from tobacco production which started around 2004. Nevertheless it was only in 2010 that the Malaysian government seriously accepted kenaf as the nation’s seventh commodity, through the establishment of the National Kenaf and Tobacco Board. The world kenaf production is dominated by India, followed by China. The production in Malaysia is relatively small yet.

SISAL FIBER

Sisal (*Agave sisalana Perr)* is a monocotyledonous plant that belongs to the *Agavaceae* family. Sisal is a native plant of Mexico's Yucatan peninsula. Agave fourcroydes plant produces a similar fiber called henequen. These fibers belong to the hard fiber group. The first stage of the harvesting process is the periodic cutting of the sisal leaves. Then the cut leaves are individually fed into a decorticator in which the pulp material is removed, leaving the fibers. In Tanzania and Kenya processing of sisal leaves takes place in large centrally-located plants. In this system decorticating machines with running water are used to wash away residues. After decortication the fibers are soaked in water for some time and then sun dried. With further cleaning by brushing to be baled for transport.

Sisal is used mainly in twine and ropes production for use in agriculture. New applications are emerging for speciality paper, filters, geotextiles, mattresses, carpets and wall coverings. But also in composite materials. The by-products from sisal fiber extraction are used for producing bio-gas for electricity production. Research is being conducted to explore the use of sisal sub-streams in the production of pharmaceutical ingredients.

Sisal is a hardy tropical plant that can survive in a variety of warm climates, including areas with little rainfall and unsuitable for other crops. Sisal is cultivated for its fibers in Brazil, Tanzania, China, Cuba, Kenya, Haiti, Madagascar and Mexico. In Tanzania and Kenya sisal is predominantly a plantation crop, although some volume is produced by smallholders. Production in Brazil is largely in the hands of small farmers.

The world sisal production in quantity terms is dominated by Brazil followed by Tanzania and Kenya. Many decades ago Tanzania used to be leading producer, when nearly 30% of the working population of Tanzania was dependent on sisal fiber production. In 2014, Brazil is the largest international producer of sisal fiber.

06

HOLDING IT TOGETHER: POLYMER MATRIX

Why use up the forests which were centuries in the making and the mines which required ages to lay down, if we can get the equivalent of forest and mineral products in the annual growth of the fields?

Henry Ford

Buddha - Probably Amitabha.

Tang dynasty. Early 7th century. China.

Production: Core possibly of wood covered with clay & then with hemp cloth. Finished with resin/lacquer. Wood core then removed.

Word *Lacquer* originates from Sanskrit and also means wax and resinous secretion of insects. Possibly known as Shellac.

Source: Metropolitan Museum

What is this chapter about?

Polymers, in addition to natural fibers, are the key materials used in composites. Man-made polymers for composite application can be manufactured from fossil fuel based components, renewable or natural materials or a combination of these two materials. The polymers used in composites can be of the type **Thermoplastics, Thermosets or Elastomers**. These polymers are characterized according to their chemical properties and behaviour. Intuitively people would associate natural fibers with "greenness" but polymers not.

In the context of the industrial revolution the polymer industry as it is known today started with biobased feed stocks and even biobased composite materials. Natural polymers and natural fiber composites were used in Asia and in South-America even centuries Before Christ (BC). In the late 1800 and early 1900 chemists and businessmen in Europe and USA created the polymers or manmade materials industry as known today. The reason was that feedstock like horn, tortoise shell, waxes etc. were becoming scarce for producing natural polymer products. With the oil boom, fossil fuel based polymers based on hydrocarbon chemistry made their entrance. Cheap plastics were produced and the rest is history. However in the current context of resource constraints and environmental pressures scientists are turning back again to feedstocks based on natural and renewable materials. Carbohydrate chemistry is driving biobased material development. It seems that bioplastic is being resurrected, to serve the material needs of humanity.

The well reputed materials scientist Mike Ashby provides an interesting timeline of the change in mans dependency on natural to non-renewable resources. See Figure 6.1. However, the attentive reader would notice that the graph applies mostly to the European and western situation. Asia, near Asia and the middle east are not a part of the European "dark ages". These regions were already enlightened and used different materials in many sophisticated ways.

In recent years the popularity of so called "Biobased" materials is increasing. Product designers who wish to use "Eco" or "Green" materials may consider the use of biobased polymers in composites. Therefore the key focus of this chapter will be on some essential aspects of biobased materials.

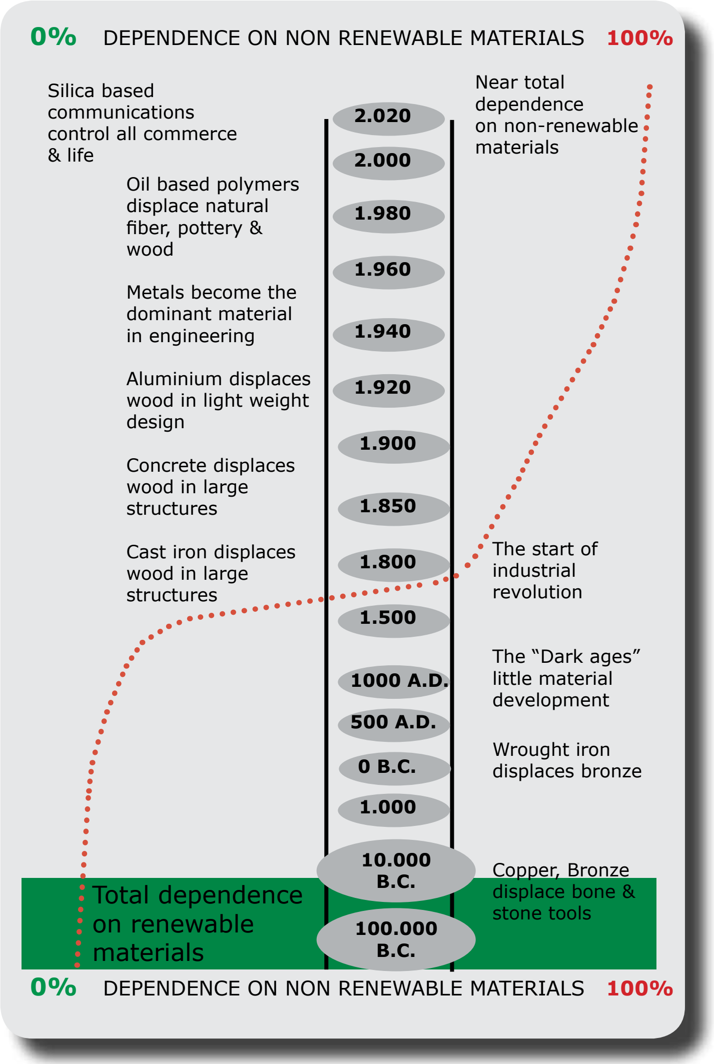


Figure 6.1: Dependency on type of materials

Even though Natural Fiber Composites (NFC) can be made with fossil fuel based polymers, the objective is to make products with Biocomposites (biobased) and ultimately Green Composites, based on renewable materials only. Therefore it could be important for product designers to understand the concept of Biobased materials and how they relate to bioplastics.

This chapter is about polymers, also called the Matrix when used in composites. It provides a simple introduction to the use of polymer matrix. The chapter is an introduction to the key concepts related to polymers, plastics and bioplastics to be used in NFC products. Hopefully it will enable the non-technical reader to understand the key concepts of polymers and enable him or her to understand the functions of polymers in composites. It should help the product designer to understand the jargon of polymer industry, both fossil fuel based plastics and renewable materials based polymers. Especially Biobased materials could be confusing or even misleading in some cases. The subject is dealt with in very general terms only, sparing the reader the technicalities of chemistry and biochemistry. The interested reader can refer to many excellent books available on these topics.

The chapter starts with an introduction to polymers and plastics in general, to be followed by biobased materials and biopolymers. Finally the use of polymers in NFC is presented

Additionally in *appendix 1* more general technical information is provided on polymers.

POLYMERS AND PLASTICS

The evolutionary processes of nature, spanning millions of years, have created natural polymers. These natural polymers have been in use by humans for thousands of years. Bones, horns, the sap of various trees (amber), waxes etc are all polymeric materials used by man. These materials were shaped into artefacts or used in other forms. For example a milk derivative called Casein was and still is used to produce buttons. Shellac was used to produce early gramophone records. In Asia Shellac was used particularly by the Chinese to varnish artifacts. Many such materials are used even today.

Source: Susan Mossman - Early Plastics:
Perspectives 1850 – 1950
Science Museum London 1997

Powder Flask
Tibetan or Mongolian, Leather, horn, Shellac, gold & pigments.
Possibly 16th-17th century.
Source: The Metropolitan Museum

A celluloid dressing table set made about 1910

As some of these natural materials, for example horn, ivory, tortoise shell, were getting difficult to obtain, people started to experiment with alternative materials. The early plastics were modifications of natural polymers. Only with the development of organic chemistry did large scale production of synthetic or man-made polymer did become fully industrialized. These developments enabled “ordinary citizens” to purchase products and in a way that could be considered the early days of mass consumption.

Essentially “poly” means many and “mer” means units. Polymer means many units.
Polymers are organic, carbon based compounds, chemists would say. Polymers are composed of large molecules, with high relative molecular mass, of repeating smaller units linked into long chains. The smaller units are monomers, which are bonded covalently to from polymers. Polymers are often called macromolecules because they are very long molecules formed by joining many thousands of small units of monomers in a process known as polymerization. Polyethylene is formed by polymerizing ethylene molecules.

In the context of plastics, polymers are synthetic or artificial materials. The types of monomers and linkages can be manipulated to produce a wide range of materials with properties such as strength, flexibility, density, transparency, chemical stability etc. Essentially the differences in polymers can be due to the type of monomers used and how the polymer chains inter-act or are bonded together.
The building blocks, i.e. monomers, are referred to as organic (in the vocabulary of chemists and not in the modern context of food or farming) molecules based on carbon. The building blocks are mainly derived from petroleum (oil) or natural gas. Generally polymers are based on Hydrocarbons.
But polymers can also be made natural or from plant material such as rubber, cotton, wood, banana peel, corn or from animal origin such as silk or wood. Even other “organic” materials such as chicken feathers, bones etc. can be used to produce polymers. All these are Carbohydrates and Protein based polymers.

From a structural view point, the most important properties of polymers are determined by:

- the rigidity of the polymer molecules.
- attracting forces between the chains.
- the crystalline domains i.e. the degree to which the chains form them.
- the degree of cross-linking between the chains.

Thermoset, Thermoplastics and Elastomeric polymers

In Thermoset polymers the links of the chains are cross-linked. A key characteristic of cross-links is the formation of strong bonds between the chains. Once the cross links are set then it is not possible to process the material further. When it is heated in an attempt to reshape it will break-down, also in chemical composition. Cross linked polymers tend be to more rigid and strong. Thermoset polymers can be moulded when they are heated, But once they cool down they cannot be reheated and moulded again.

Thermoplastics can be heated and moulded. Thermoplastic polymers have relatively weak links between the chains. This means they tend to soften when heated and therefore can be remoulded. This process - theoretically - can be repeated several times.

There are polymers that can absorb the energy of a blow and pass it along the chains. Hence they will not get damaged or crack. They may flex and twist their chains. These are called Elastomeric polymers. Elastomers could be subjected to forces and they would generally return to the original state.

Modifying polymers

The basic polymer properties could be modified in many different ways to suit specific purpose. Without getting into too many details the typical additives to polymers could be:

- Colourants (e.g. improve the appearance)
- Fillers (e.g. reduce costs)
- Protective agents (e.g. against light)
- Impact modifiers (e.g. improve impact resistance)
- Plasticisers (e.g. increase flexibility)
- Lubricants (e.g. flow more flexibly)

Plastics are polymers but not all polymers are plastics

Plastics are artificial or synthetic polymeric materials made by man. The roots of the word Plastic are in the Greek word plasticos, which means “capable of being shaped or moulded by heat”. Plastos in Greek means moulded. From the view point of chemistry, polymers is the term referring to all plastic materials. But not all polymers are plastics. For example DNA is a polymer too.

The Greeks only invented the word “plastos”, but not “plastics” as the material, as we know it today. Often the beginnings of the plastics as a material and plastic industry are unclear. Reference is made to John O’Brisset, who in 1712, made a moulded snuff boxes from horn. In 1868 John Wesley Hyatt of USA invented Cellulose Nitrate, which he named Celluloid. However, Alexander Parks of UK had displayed Parkesine at the Great International Exhibition in London, made from cellulose from wood flour and cotton waste and nitric acid, in 1862. It was possible to produce high quality products with Parkesine but Parks could not make the material as successful as Hyatt did with Celluloid. Hyatt participated in a competition to produce billiard balls with an alternative material due to shortage of ivory. He won the competition and set up a business to produce Celluloid. It was soon discovered that Celluloid billiard balls when banged together caused an explosion. In a modified form Celluloid is used in table tennis or Ping Pong balls. Celluloid is the first semi-synthetic commercially successful thermoplastic material.

In 1907 a Belgium chemist living in America called Leo Baekeland, developed the synthetic plastic “Oxybenzylmethyleneglycolanhydryde ”; much better known under the trade name of ‘Bakelite’!

Bakelite products - Products made available by courtesy of Stadsmuseum Zoetermeer, The Netherlands

The 2nd wave of plastics: Bioplastics

After the initial success of imitations of some natural processes by chemists, they never stopped manipulating molecules to design new materials with specific functions for different uses. This did bring forth many man-made materials that were useful. In some cases, if not in many, these man-made materials resulted, and are still resulting, in disastrous consequences to nature. Natural processes have elegant solutions that fulfill functions as they have to and at the end of life return to where they came from - nature. But man-made plastics on the other hand could not be simply and naturally broken down. Millions of tons accumulate in nature. In an effort to maintain the wide range of applications of plastics but to minimize the environmental impact, chemists are turning to renewable materials.

So polymers and plastics maybe entering a 2nd wave of "innovation" - the bioplastics!

Source: National geographic and WWF

BIOPLASTICS AND BIOBASED MATERIALS

From a product designer perspective it is suggested to recognize two key aspects when considering a polymeric matrix material for NFC application, namely:

√ Understand the difference between bioplastics and Biobased-materials.

√ The characterization of decomposition of the polymeric material in terms of time and environmental conditions. The key terms are biodegradation and compostability.

Bioplastics
Biopolymers are naturally occurring materials and Bioplastics are man-made materials.
Bioplastics can be produced from renewable feed-stock. Even though there is a large availability of agro feed stocks to produce bioplastics, a balance should be found in the allocation for use as food, fuel and feed. It is not desirable to divert renewable materials that are food for use as fuel or feedstock for materials. However agro-wastes of food can be used as feedstock for fuel and material production.

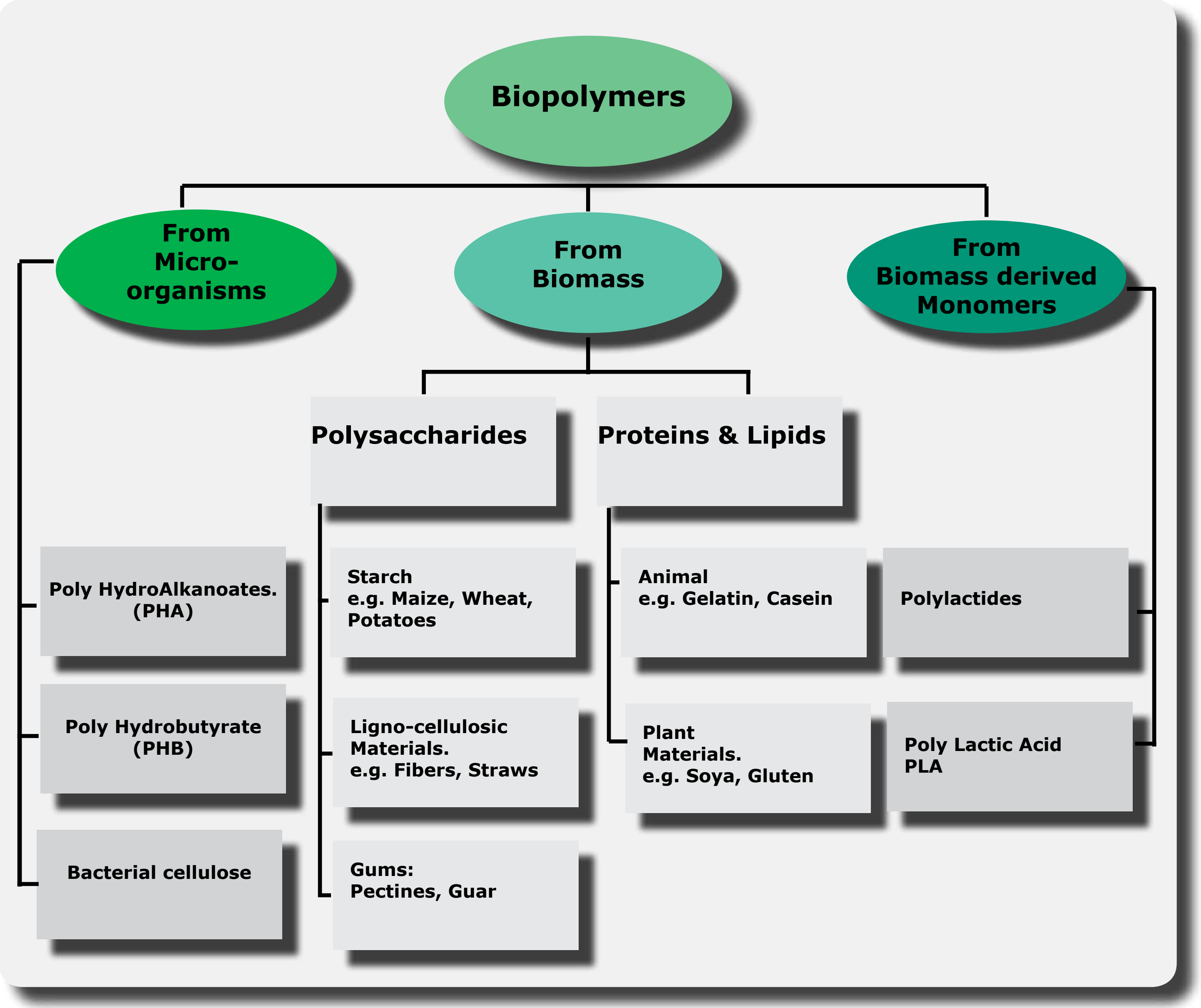
The challenge is to have a wide range of bio-plastics that could meet the different properties needed for different applications. Even though the use of natural (bio)polymers goes back many centuries, the fossil based polymer development has been more dominant. Mainly in the past 100-odd years. Therefore the fossil based polymers are numerous compared to bioplastics.

Bioplastics can be:

- Directly derived from biomass (e.g. Polysaccahrides. Lingnocellulose, Proteins & Lipids)
- Synthesized from bio-derived monomers (Polylactate, other polyesters. e.g. PLA)
- Produced by micro-organisms (Polyhydroxyalkonoates e.g. PHA)

Figure 6.2. shows the various possibilities of Biopolymer production methods and the origins.

Figure 6.2: Origins and sources of Biopolymers

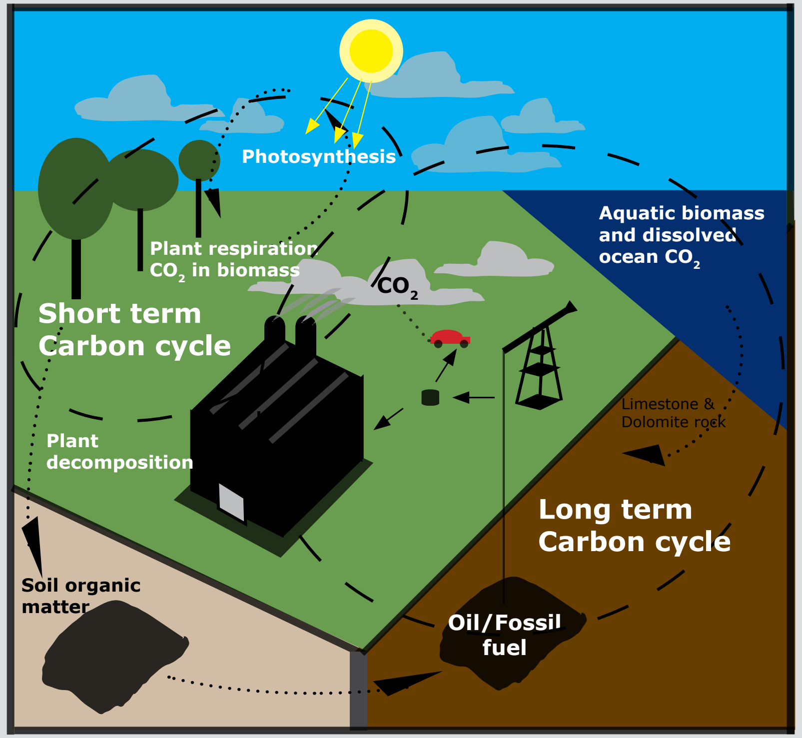


There has been a drive to blend bioplastics and fossil fuel based polymers. Under certain conditions these are called Biobased materials. Even though it may seem obvious, it is important to understand the terms that are being used to describe materials: namely "biomaterials" and "Biobased-materials".

Biogenic matter is defined as material "produced in natural processes by living organisms but not fossilised, or derived from fossil resources" (European Committee for Standardisation, 2006a). Biomaterials can be understood as materials resulting from natural processes. Carbon seems to be the main compound of attention, as far as polymers and plastics are concerned.

It is mainly about bio/renewable feed stock, with short carbon cycles in contrast to fossil carbon/petro carbon, which are the result of long carbon cycle.
The question is what is short and what is long time? Bio/Renewable carbon feedstock can have a cycle of 1 to 10 years. While the fossil/petro carbon cycle can be greater than 1.000.000 years.

Figure 6.3: Simplified illustration of Short and Long Carbon Cycle



Business interests, and even political motivations, have provided modified views on what is called Biobased materials.

Essentially Biobased materials may contain:

- 100% Biogenic carbon (short cycle or new carbon, with ^{14}C isotope)
- Mix of biogenic carbon with fossil/Petro based carbon (long cycle or old carbon, no ^{14}C in fossil carbon)

But to obtain the classification “Biobased” the materials should have a certain amount of biogenic carbon. This biogenic carbon is identified by its ^{14}C signature. There are standard test methods developed (for example ASTM D6866 or CEN?TS 16295) to determine the presence of ^{14}C isotope. The proportional content of new carbon (^{14}C) and old carbon ^{12}C (as in fossil/Petro) is measured. Based on some minimum new carbon content a certain classification is provided. For example if 20% renewable material is used then the label could be BIOBASED-20%. However, there are academic discussions about this concept. This will not be dealt with any further here.

The key point for product designers is to be able to recognize the different Biobased labels in the market place and to understand the meaning they attempt to convey.

A few examples of Biobased material lables and logos are shown in figure 6.4.

Why is time scale important?

It is to do with the levels of carbon dioxide (CO_2) - so called transformed biogenic inorganic compound - in the atmosphere. The right level of CO_2 is essential for humans to survive in the planets life giving processes. But like most things too much of it can be a problem for humans and maybe for animals and some plants too. But this does not have to be damaging to or for the planet itself. With higher CO_2 levels the planet may look different. But it may/will continue without humans on it. This is another matter and discussion all together.

To summarize: when humans pump too much CO_2 into the atmosphere than the processing capacity of the planet it could be an issue. In all fairness it should also be mentioned that the culprit is not just CO_2. Other compounds too can cause problems, for example methane. These emissions cause greenhouse effects and climate change
All this is called anthropogenic impact on the environment, meaning impact caused by human actions. This is one of the key factors that is driving “Bio/Renewable” based developments.

Figure 6.4: A few biobased labels

BIODEGRADATION AND COMPOSTING

Compostable implies that the material is biodegradable. But biodegradable DOES NOT always mean the material is compostable. This is where the “non-technical” person could be misled. What are the processes involved in biodegradation and composting of “Biobased” materials, particularly bioplastics?

Biopolymers or bioplastics can act like food for micro organisms (like bacteria, algae, fungi etc.).
The microorganisms utilize the carbon products in the Biobased materials and extract chemical energy for their living. All these take place in complex biochemical processes and pathways.

For simplicity it can be said that biodegradation consists of fragmentation and mineralization. Due to fragmentation the essential properties such as tensile strength, toughness etc. are weakened. The polymer chains are shortened and there may be mass reduction. The process of fragmentation can be by microorganisms or by non-living factors such as light, heat etc. Then the partially degraded polymers (fragments) are mineralized by microorganisms i.e. metabolized into end products, such as carbon dioxide, water, biomass etc. The key factors for biodegradation are the time needed for the mineralization and the level of mineralization. When the Biobased polymers are completely biodegraded in a short time (less than 12 weeks say) then it is referred to as compostable Biobased polymers. If the Biobased polymer is fragmented but does not mineralize or take long time to do so then its long term impact of living and non-living matter will be unknown.

Therefore the key factors that product designers must understand about biodegradation is the rate of decomposition and the degree of mineralization of the biobased polymers. When the mineralization is fully completed within the composting cycle then the biobased polymer can be considered compostable. The end products must be nontoxic too.

The most known specification for compostability is EN13432, EN14995. According to this standard specification the following requirements for compostable products apply:

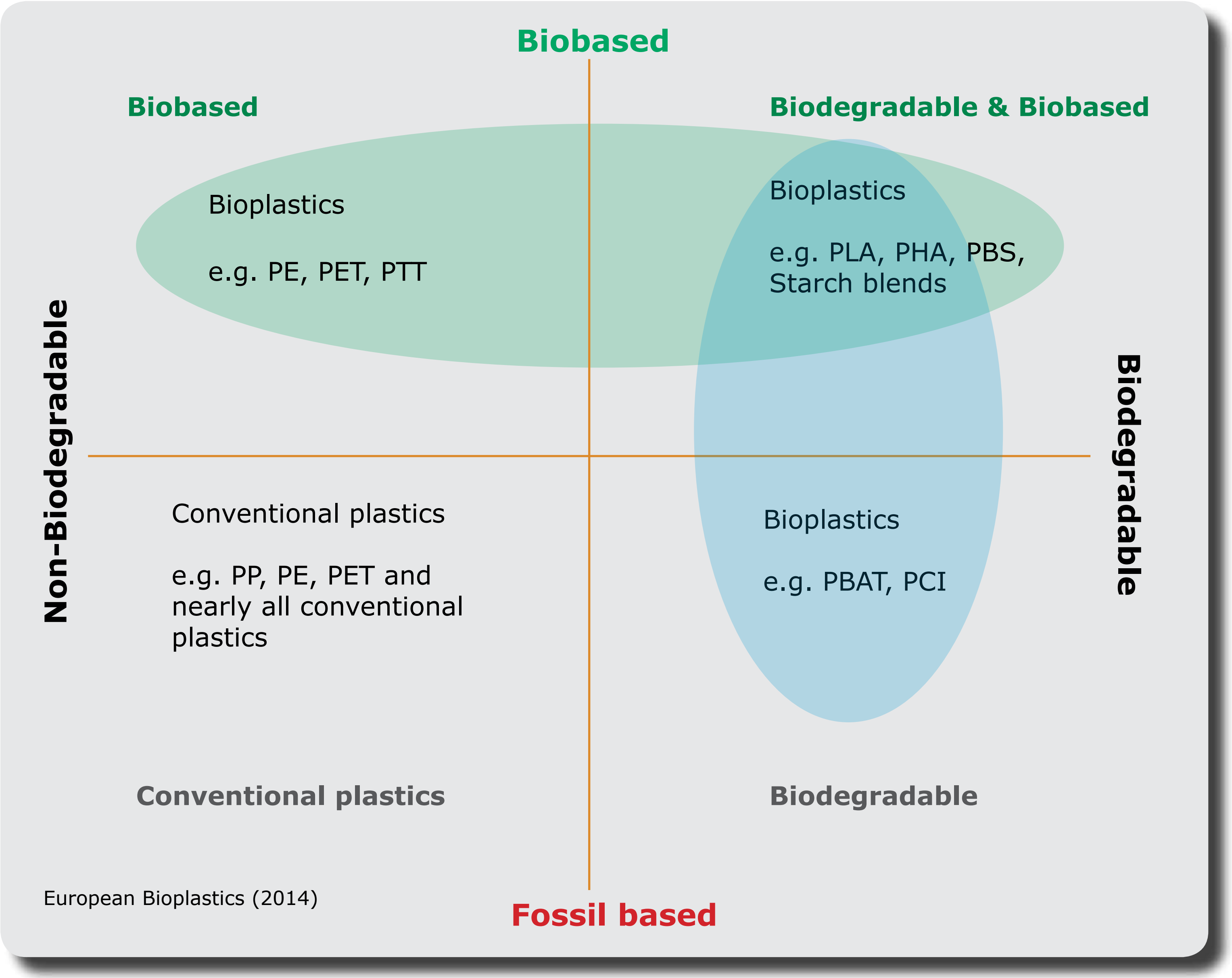
- Content of heavy metals and other elements below the limits mentioned in the standard;
- Disintegration analysis during biological treatment. 3 months (12 weeks) analysis in industrial or half industrial composting conditions should present sufficient disintegration level (not more than 10 % of dry matter may stay above 2 mm sieve);
- Biodegradation analysis - at least 90 % of the organic carbon MUST be converted into carbon dioxide within 180 days (mineralization);
- Eco toxicity analysis assessing that biological treatment is not decreasing the level of compost quality – this is determined by a plant growth test.

The above aspects share similarities with other standards such as ASTM 6400-04 and ISO 17088:2008.

Finally product designers could also come across the term Oxo-Biodegradation.
What does this mean? Oxo-Biodegradation is generally achieved by additives to the biobased polymers that support oxidation resulting in the above mentioned fragmentation i.e. decompose into smaller particles. Even though these are fragments they can continue to exist in the environment possibly causing damage and toxicity. The appropriate description for these materials would be Oxo-fragmentation. Additives are typically used in conventional plastics such as PP, PE, PET and PVC, These additives could include transition metals such as iron, manganese, cobalt etc. Generally Oxo-fragmented biobased polymers could be problematic.

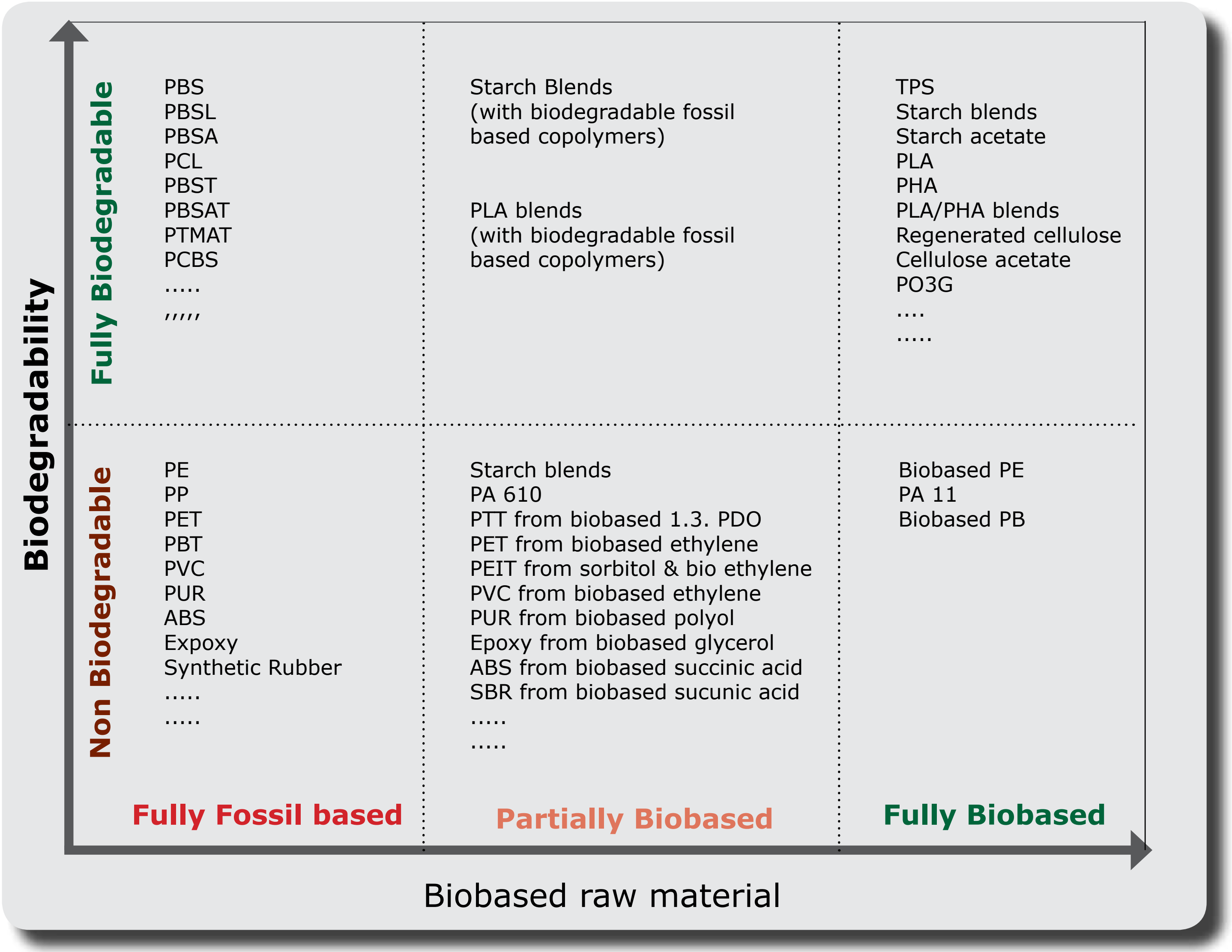
Based on the feed stock and degradability figure 6.5 illustrates the positions of some commonly used Bio-polymers. Note that some fossil-based plastics like PBAT are biodegradable, while not all biobased plastics are (like BB-PE)

Figure 6.5: Positioning Biopolymers according to feed stock and degradability



European Bioplastics (2014)

Figure 6.6: General categorization the biobased plastics: Biobased content and Biodegradability



Biodegradability	Fully Fossil based	Partially Biobased	Fully Biobased
Fully Biodegradable	PBS PBSL PBSA PCL PBST PBSAT PTMAT PCBS ..... ,,,,,	Starch Blends (with biodegradable fossil based copolymers) PLA blends (with biodegradable fossil based copolymers)	TPS Starch blends Starch acetate PLA PHA PLA/PHA blends Regenerated cellulose Cellulose acetate PO3G ....
Non Biodegradable	PE PP PET PBT PVC PUR ABS Expoxy Synthetic Rubber	Starch blends PA 610 PTT from biobased 1.3. PDO PET from biobased ethylene PEIT from sorbitol & bio ethylene PVC from biobased ethylene PUR from biobased polyol Epoxy from biobased glycerol ABS from biobased succinic acid SBR from biobased sucunic acid	Biobased PE PA 11 Biobased PB

Source: Martin Patel et. al. November 2009, Products overview & markets projection of emerging biobased plastics.

Some common terms related to the concepts of Biodegradation and Composting

In order to get to grips with this subject the starting point could be a brief clarification of some related terms:

Aerobic decomposition is biological decomposition in presence of oxygen or air where carbon is converted to carbon, methane and biomass.

Anaerobic decomposition is biological decomposition in absence of oxygen or air where carbon is converted to carbon, dioxide and biomass.

Biomass, also renewable resource, are substances of biological origin, but excluding geological formations and fossilized biological matter.

Degradation can be considered as an irreversible process in which material undergoes changes. These can be physical, chemical and/or biochemical changes.

Biodegradation is when materials degrade significantly through biological processes.

Ultimate Biodegradation is when materials fully transform through biological processes into nontoxic carbonaceous soil, water, carbon dioxide or methane. Sometimes reference is made to mineralization and/or biomass formation.

Biodegradability the degree of biodegradation leading to mineralization and biomass formation.

Mineralization the conversion of materials to naturally occurring inorganic substances and gasses.

Composting biodegradation under specified time and environmental conditions and must result in non-toxic substances like biomass, water etc. Typically defined in standards such as EN13432, EN 14996, ISO 17088:2008 and ASTM 6400-04.

Oxo-degradation Degradation and fragmentation of the material caused by specific additives to conventional non-biodegrabale plastics. The key step of mineralization often not proven for these materials.

Photo-degradation degradation by light

POLYMERS IN NATURAL FIBER COMPOSITES

Unlike natural fibers that are renewable materials, polymers can be both fossil/petro and renewable based and/or can be a mix of the two. This leads to issues such as product identification and labelling. In addition there are other issues such as biodegradability and compostability that need to be taken into consideration. This is important for end-of-life cycle of the products. Now that background information on these topics has already been provided in the previous section. In this section the types of polymer matrix used in NFC will be presented.

In the vocabulary of composites polymers, be it renewable or fossil/petro based, are referred to as the matrix. A matrix is a homogenous (continuous phase) medium in which "other materials" are embedded. In the case of Natural Fiber Composites, the "other material" is natural fibers, such as abaca, coir, flax, hemp, jute or sisal fiber.

Why mix a polymer and a natural fiber at all?

Generally when both the fibers and matrix are renewable based the composite is called biocomposite or green composite. However, at present, there seems to be no clear definition for these materials other than a biobased definition and the related labeling as discussed in the previous sections. Irrespective of the origin of the polymer used, the technical reasons to combine natural fibers and polymers matrix are:

√ **Reinforcement:** the natural fibers can improve the properties of the polymers. In this case the natural fibers have a reinforcing function.

√ **Binding:** Polymers could be used as a binder to provide shape and structural stability to the natural fiber structure or preform. The natural fibers can be in loose fibers, woven of nonwoven forms.

In any product design process material choice is a key consideration. This aspect was already discussed in chapter 2. In the context of NFC the considerations could be technical, design and economic.

For example factors that could influence the choice of polymer matrix would be:

√ the number of products to be manufactured.
√ the size of the product or component to be manufactured.
√ the shape of the product or component to be manufactured.
√ the environmental conditions under which the NFC product would have to perform.
√ none engineering factors such as touch and feel or appearance.
√ end-of-life cycle consideration (biodegradability, compostability, recyclability etc).

Not going to the moon: The misplaced notion of the properties of natural fiber composites

Composites technology due to its recent origin (20th century) in the aerospace applications seems to be mainly driven by engineering properties such as strength, stiffness and weight. This focus is mainly based on the use of man-made fibers such as glass fiber and carbon fiber and thermoset polymers. These applications are structural or load bearing applications. But not every part in an aeroplane needs to be load bearing. The focus on structural parts has led academics and researchers to try to replace or substitute glass fibers or carbon fibers with natural fibers in composites and claims of disappointing results. This instead of maximizing the wide range of engineering and aesthetic properties natural fibers offer for product design. The substitution strategy has led to the disproportionate focus on strength and stiffness of natural fiber composite materials. Even in the aerospace industry there is huge potential for NFC application, for example in the non-structural interior or cabin parts of aeroplanes. Of course the smoke, toxicity and flame related specifications need to be satisfied.

Natural Fiber Composites can be used in many industrial and consumer applications where the technical requirements of the aerospace industry will not be relevant at all. The requirements of engineering properties in many applications could be different and can be satisfied by NFC. In addition to engineering properties other design considerations such as the aesthetics and environmental aspects of the materials used can be equally important. In a high end application such as car seat production elasticity, resilience and comfort are key technical parameters. The car seats made of coir (coconut) fiber combined with natural rubber latex as the elastomeric polymer fully meet all the engineering specifications. This application goes back several decades where reputed car manufacturers such as Daimler Benz use these materials for their technical, environmental and comfort properties. In an another example, the combination of coir (coconut) fiber and latex rubber has been used as packaging material for ammunition during transportation. The non-static properties were the key consideration in this application. In recent years the material has been used by a well known retailer chain in the Netherlands to package bio-eggs; the packaging material was a major consideration in the environmental and aesthetic aspect to enhance the product brand in a holistic manner. In addition to the functional purpose as packaging, the consumers of this egg packaging were reported to have lots of funs using the material in their hobby activities. These are just a few examples to illustrate the wide potential of NFC in different applications and industries.

The functionalities of matrix

Polymer matrix in composites will need to satisfy many functional requirements. Typical requirements could include but are not limited to:

- Mechanical properties
- Chemical properties
- Toxicity and safety
- Processing and ease of use
- Environmental properties
- Recyclability and end-of-life disposal

Engineering in daily life

Stretch it, how much stretch before it breaks? (Measure of strength)

Push on it, how much does it bend? (Measure of stiffness)

Hit it hard, does it break easily? (Measure of brittleness)

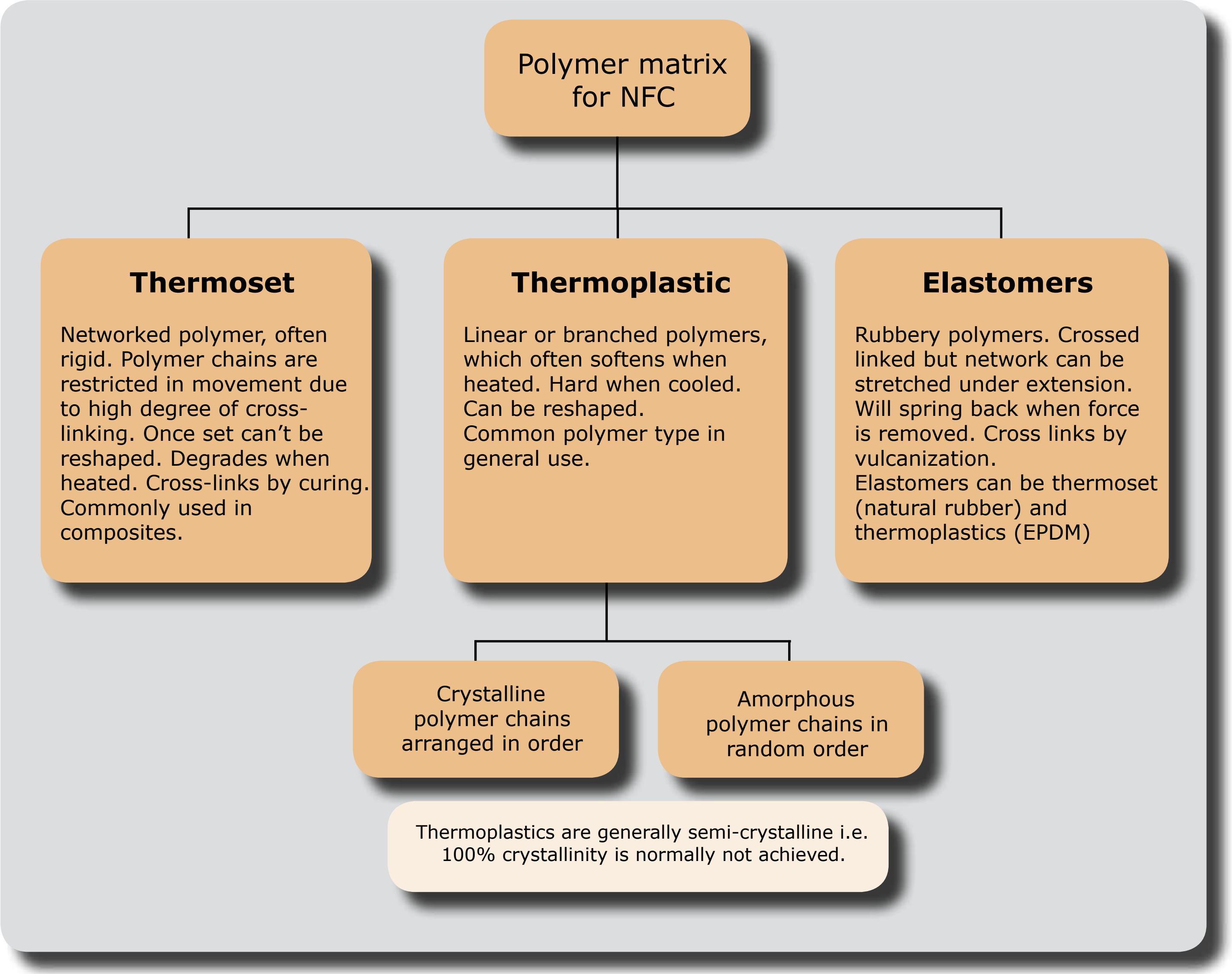
Is it hard or soft?

Does it hold up well under repeated stress?

The polymer matrix for NFC applications: Thermoset, Thermoplastic and Elastomers

The common polymer matrix used for NFC are the types thermoset, thermoplastics and elastomers. The generic characteristics are illustrated in figure 6.7.

Figure 6.7: The polymer matrix used in composites



Polymer matrix for NFC

Thermoset

Networked polymer, often rigid. Polymer chains are restricted in movement due to high degree of cross-linking. Once set can't be reshaped. Degrades when heated. Cross-links by curing. Commonly used in composites.

Thermoplastic

Linear or branched polymers, which often softens when heated. Hard when cooled. Can be reshaped. Common polymer type in general use.

Elastomers

Rubbery polymers. Crossed linked but network can be stretched under extension. Will spring back when force is removed. Cross links by vulcanization. Elastomers can be thermoset (natural rubber) and thermoplastics (EPDM)

Crystalline polymer chains arranged in order

Amorphous polymer chains in random order

Thermoplastics are generally semi-crystalline i.e. 100% crystallinity is normally not achieved.

A BRIEF SUMMARY: SOME GENERAL CHARACTERISTICS OF THERMOSETS, THERMOPLASTICS AND ELASTOMERS

THERMOPLASTIC	THERMOSET	ELASTOMER
More elastic and tends to be relatively softer	Tends to be hard. Permanently set	Generally soft
Could be recycled	Not possible or difficult to recycle	Difficult to recycle
Not brittle	Brittle	High elongation
Tends to be high in coefficient of expansion	Low coefficient of expansion	
Sensitive to temperature	Less temperature sensitive (within limits)	
Tends to lose form when heated and when cooled gets hard. Can be melted	Tends to keep the form when heated but at high temperatures gets damaged	
Long shelf-life	May need special storage	
Major share of polymer markets	Major share in composites markets	Low market share in composites

THE TYPICAL CANDIDATE POLYMERS FOR NFC: THERMOSETS, THERMOPLASTICS AND ELASTOMERS

The common types of polymers used as the matrix in composites applications are shown in the following table.

THERMOPLASTIC	THERMOSET	ELASTOMER
Polypropylene (PP)	Polyester (PE)	Natural Rubber
Polyethylene (PE)	Epoxy (EP)	Styrene Butadiene Rubber (SBR)
Polyvinyl chloride (PVC)	Phenolic (PF)	Synthetic Polyisoprene (IR)
Biobased PE, PVC, etc.	Polyurethane (PUR)	Nitrile butadiene rubber (NBR)
Thermoplastic starch blends	Furan resins	
PLA	Various Bio resins	

SOME GENERAL CHARACTERISTICS OF THERMOSETS POLYMERS: POLYESTER & EPOXY

CHARACTERISTICS	POLYESTER	EPOXY
Flexural strength	Good	Best
Tensile strength	Good	Best
Elongation %	Good	Lowest
Hardness	Good	Best
Pot life	Less than 10 minutes	Less than 20 minutes
Working time	Less than 30 minutes	45 minutes to 5 hours
Shelf life	12 - 24 months	Less than 24 months
Catalyst required	Yes	2 component
Cure time	Less than 7/8 hours	Few days (less than 5/6)

Summary

Plastics and Bioplastics are man-made polymeric materials. Biobased materials can be of fossil/ petro origins, renewable origins or a mix of these two types of feedstocks. These materials have become known as biobased materials. Bioplastics can be biodegradable and compostable. Some bioplastics are degradable but not compostable. But not all bioplastics are biodegradable. Test methods are available to identify the renewable material component of biobased materials. Different countries have developed certification schemes to label biobased materials.

Biobased and fossil fuel based polymers can be the types Thermoset, Thermoplastics and Elastomers. The polymers, also known as matrix in composites, and natural fiber are combined for reinforcement or binding. The natural fiber can be used to reinforce the polymers and enhance its properties. Alternatively the polymers can be used to hold the natural fiber products or preform together to provide structural stability, shape/form and coherence.

Thermoset is the most commonly used polymer in composites applications. Efforts are being made to use thermoplastics in composites. This is because it is the most widely used polymer and has a shorter processing cycle time. Each of these polymer types exhibit different chemical, processing and mechanical properties. There are several proven processing techniques that can be used to produce NFC products based on these polymers.

In product designer consideration the properties of NFC should not be restricted to strength and stiffness alone. Other engineering properties such as elasticity, electrical etc. can be important engineering properties as well. High-end NFC products based on these properties are already in the market place. In addition to engineering and systems properties such as environmental impact, comfort and sensorial properties can be important in product design. Finally as natural materials NFC can contribute towards sustainability. These products can enhance the overall product brand image by a fascinating narrative and story of the materials origins and use. NFC can contribute towards biobased economies.

07

TECHNOLOGY & PROCESSES: MAKING IT HAPPEN

“Things should be made as simple as possible, but not any simpler.”

Albert Einstein

NATURAL FIBER COMPOSITES PRODUCTION PROCESSES

Natural fibers are composite materials produced by nature in the most ingenious and even mysterious ways. Nature sets to motion processes to perfectly fulfill all the requirements for the existence and continuity of the particular species of plant crop. All coded in the DNA, the biochemical software, of the plant.
Humans use materials nature offers and process them in ways to suit their needs. This chapter is an introduction to the basic and commonly used processes to combine natural fibers and polymers to form semi-finished and finished Natural Fiber Composites (NFC) products. These products could be components - used in combination with other components to form a final product - or an end product.

In chapters 5 and 6, the basic ingredients of NFC were discussed. In this chapter the basic mechanisms of the NFC production processes are introduced. The objective is to introduce the wide range of options available. Also to encourage the product designer to take into account, at an early stage of designs process, how the product should be made.

NFC Production Process Consideration

The design process considerations for NFC are not any different to other materials. The only difficulty is that the know-how of production methods is rather limited or propriety i.e. trade-secret.
The general considerations for selecting a production method are:

√ the rate of production and the amount to be produced per year for example.
√ the form/shape/size of the component or product.
√ the required mechanical and aesthetic properties.
√ the economics and market aspects.
√ In addition to the above aspects, the environmental and safety aspects could also play a role.

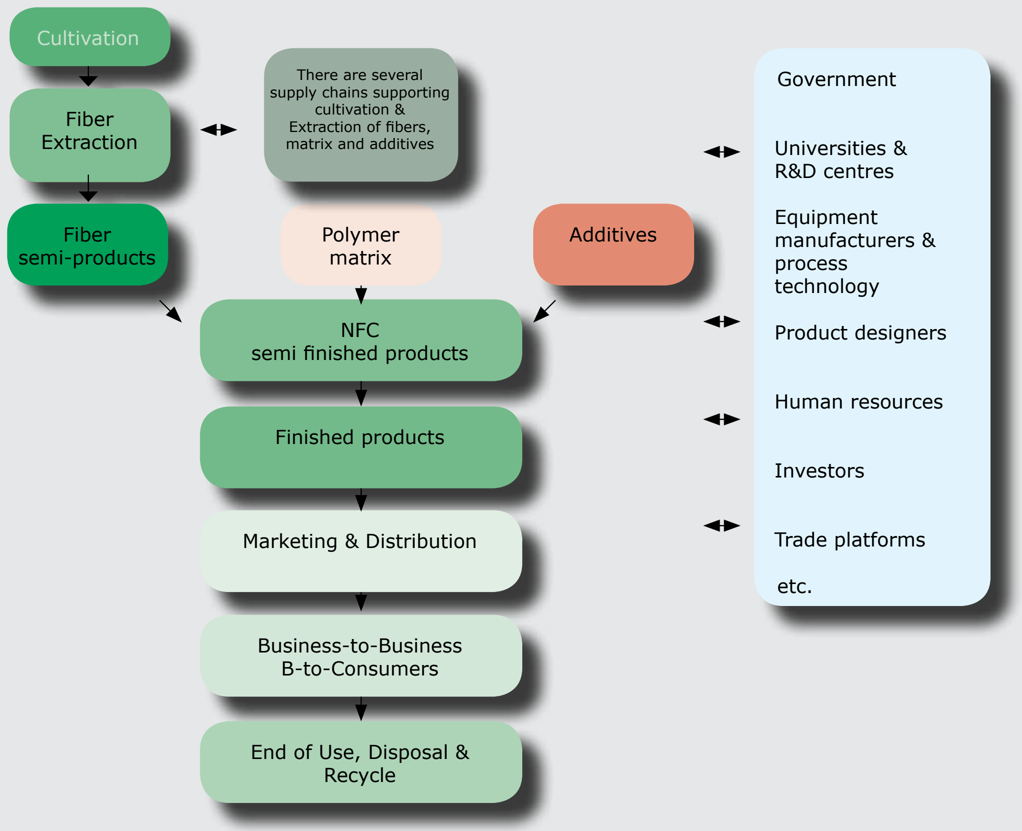
Depending on the above mentioned factors the choice would be made as to the polymer to be used. Generally it is either thermoset or thermoplastic. But elastomeric polymers can be used too. Similar to the wide range of polymers there is a wide range of possibilities of natural fiber materials for NFC processing. For example short fibers can be used to produce injection moulding granules. Complex 3-D architecture of woven natural fiber textiles can be used for demanding applications. One other major consideration would be the aspirations of the product designer in high-lighting the naturalness of NFC products. Would he or she go for the “plastic-ness” that seems to have become the norm of “design products” or the naturalness and diversity nature offers. In any case the artefact should fulfill its functional requirements.

Manufacturing Processes of Natural Fiber Composites

NFC products can be made using very simple manual techniques or very technology intensive methods. Product designers should be aware that they can make beautiful NFC or even 100% biocomposite products literally in their backyard or garage. In the current context NFC production methods depend on the techniques of composites made by using man-made materials such as glass fibers and polymers. One of the key points often neglected both in business and academia is that without proper equipment the production of NFC could face difficulties. Equipment manufacturers, for understandable reasons, invest in improvement of techniques and processes for man-made materials, that is where the big business is. So depending on the type of product, NFC production often depends on existing methods. These methods could sometimes need minor modification to suit the characteristics of NFC. But a wide range of NFC products can be produced by using existing processes.

To make NFC products a truly multidisciplinary approach is needed where all parties in the value chain work together i.e. from materials suppliers, equipment producers, processing companies, academia and end customers. Figure 71. illustrates in a highly simplified manner the various stakholders in the supply and value chain of NFC.
Undoubtedly the equipment and process methods of composite manufacturing are driven by the traditional composites industry and OEM in markets such as aerospace, automotive & transportation, wind energy, marine etc. Therefore a note of caution is needed. The techniques mentioned in this chapter are only a limited selection as an introduction to the possibilities. In practice there can be variations and combinations of methods. In the highly competitive international markets, the traditional composite equipment industry is constantly improving and coming up with new techniques. There is a degree of competition between the thermoplastic and thermoset suppliers as well. The most important aspect to take into consideration with NFC manufacturing are the maximum processing temperature and the moisture content of natural fibers. There are several ways to depict the wide range of composite manufacturing techniques. In the following section each technique is briefly described so that the product designer has a general comprehension of the method. The interested reader could refer to many engineering books and related publications to get an in-depth understanding of the different process.

Figure 7.1: Highly simplified illustration of NFC supply chain and key players



Hand Lay-Up (Hand Laminating)

Probably the most oldest, simplest and traditional method to product designers to make NFC products.

Description	Natural fiber material & Matrix	Advantages	Disadvantages	Typical products/ markets
Release agent is applied to the mould. Complemented by a Gel-Coat to improve the surface finish and aesthetic effect. Reinforcement placed into mould. Resin applied by brushing, pouring or spraying. The air is removed by rollers. Layering of NF reinforcement to desired properties. Curing at ambient conditions, mostly without additional heat. Cure time of resin could be improved by additives like accelerators and catalysts.	Non-woven & Woven mats. Polyesters & Epoxies. Additives for improved interface bonding.	Ease of use. Low cost tools. Large size parts. Inclusion of inserts. Good properties.	Labour intensive. Depends on the skills of the person. This can impact product properties. Emissions.	Marine. Furniture. Construction & Housing. Tanks & Pools. Transportation. Prototype of moulds. Flat and structured sheets.

SPRAY-UP

Description	Natural fiber material & Matrix	Advantages	Disadvantages	Typical products/ markets
Release agent is applied to the mould. Complemented by a Gel-Coat to improve the surface finish and aesthetic effect. NF reinforcement as roving is cut within a nozzle before being sprayed along with the Resin into the mould. The entrapped air is removed by rollers. Additional reinforcement and resin added to desired properties. NF mats can be incorporated to improve properties of specific areas. Curing at ambient conditions, mostly without additional heat. Cure time of resin could be improved by additives like accelerators and catalysts. Increasingly over-taken by Resin Transfer Moulding (RTM) methods.	NF roving Can be complemented by Non-woven & Woven mats. Polyesters & Epoxies. Additives for improved interface bonding.	Ease of use. Less labour intensive compared to hand lay-up. Low cost tools. Large size parts. Inclusion of inserts.	Lesser properties than Hand lay-up due to shorter fibers. Emissions.	Marine. Furniture. Construction & Housing. Tanks & Pools. Transportation. Prototype of moulds. Flat and structured sheets.

VACUUM ASSISTED RESIN INFUSION

Description	Natural fiber material & Matrix	Advantages	Disadvantages	Typical products/ markets
The easiest method to produce quality NFC products. Release agent is applied to the mould. Complemented by a Gel-Coat to improve the surface finish and aesthetic effect. Reinforcement placed into mould. Several layers of complimentary sheets are used to ensure proper wetting and flow of resin. Finally covered by a vacuum bag. All edges are sealed to ensure no leakages and to maintain vacuum in the system. The air is removed by vacuum system prior to introducing resin. Resin is infused and transferred through the woven or non-woven NF layers. Curing at ambient conditions, mostly without additional heat. Curing can also be in special ovens or autoclave. Cure time of resin could be improved by additives like accelerators and catalysts.	Non-woven & Woven mats. Polyesters & Epoxies. Additives for improved interface bonding. Several complimentary Materials.	Ease of use. Low cost tools. Large size parts. Complex parts. Narrow tolerances. Uniformity of fiber loading. Inclusion of inserts. Generally low emissions due to closed moulds. Good properties.	Labour intensive. Depends on the skills of the person. This can impact product properties.	Marine. Furniture. Construction & Housing. Tanks & Pools. Transportation. Prototype of moulds. Flat and structured sheets.

RESIN TRANSFER MOULDING

Description	Natural fiber material & Matrix	Advantages	Disadvantages	Typical products/markets
A closed mould method. Similar to VARI. Release agent is applied to the mould. Complemented by a Gel-Coat to improve the surface finish and aesthetic effect. Reinforcement placed into mould. The air is removed by venting points prior to introducing resin. Resin is infused and transferred through the woven or non-woven NF layers. Typical pressure is about 1,0 to 5,0 Bar. Generally the resin and the hardener are kept separately and mixed in a nozzle before infusion. Curing in the mould mostly in special ovens or with heat source. Cure time of resin could be improved by additives like accelerators and catalysts.	Non-woven & Woven mats. Polyesters & Epoxies. Additives for improved interface bonding.	Both surfaces finish quality good. Complex parts. Narrow tolerances. Higher production. Uniformity of fiber loading. Inclusion of inserts. Generally low emissions due to closed moulds.	Additional equipment and precision mould costs. Limitation of part size due to pressure requirements. Depends on the skills of the person. This can impact product properties.	Marine. Furniture. Construction & Housing. Tanks & Pools. Transportation. Prototype of moulds. Flat and structured sheets.

POUR SPRAY MOULDING

Description	Natural fiber material & Matrix	Advantages	Disadvantages	Typical products/ markets
Pour spray moulding is reaction process using Polyurethane (PUR). Generally a core material is layered on both sides with a mat. Typical sandwich structure. Also possible with mats only. The package cut to size. In a spray area the binder is deposited to both sides. The package could be fixed and spray nozzle moved. Alternatively nozzle fixed and package moves. Next the package is heated to speed the process and compressed to consolidate and shape the part. Curing in mould. Finishing materials can be used on both sides of the mould as need be. Generally the polymers are kept separately and mixed in a nozzle before spraying. The process can be fully automated.	Non-woven & Woven mats. Core material e.g. honeycomb Polynol & Isocyanate (PUR) Surface finishes	Both surfaces finish quality good. Light weight and high stiffness. Uniformity of fiber loading. Inclusion of inserts. Large parts possible. Low emission, with controlled ventilation.	Equipment costs. Limitation of part size. Handling different materials.	Automotive parts. Construction & Housing. Transportation. Flat and structured sheets.

STRUCTURAL REACTION INJECTION MOULDING (S-RIM)

Description	Natural fiber material & Matrix	Advantages	Disadvantages	Typical products/ markets
S-RIM is reaction process using Polyurethane (PUR). Reinforcement mats are placed into the mould. The reactive resins are introduced into the open mould OR injected into a closed mould. The part is cured in a heated mould. Finishing materials can be used on both sides of the mould as need be. Generally the polymers are kept separately and mixed in a nozzle before spraying. The process can be fully automated.	Non-woven & Woven mats. Polynol & Isocyanate (PUR) Additives. Surface finishes	Thin parts. Fast process. Higher production due to automation. Uniformity of fiber loading. Inclusion of inserts. Generally low emissions due to closed moulds.	Additional equipment and precision mould costs. Limitation of part size due to pressure requirements.	Automotive Consumer goods Transportation. Electronic goods. Medical. Aerospace.

LONG FIBER INJECTION MOULDING

Description	Natural fiber material & Matrix	Advantages	Disadvantages	Typical products/ markets
Developed as an alternative to S-RIM. It is reaction process using Polyurethane (PUR). Roving cut to desired length in cutter head and fibers are separated by a blowing mechanism. Subsequently the fibers are wetted with PUR in the mixing head. The mixture is introduced into the open mould. Once the mould is filled it is closed and cured. The part is cured in a heated mould. Finishing materials can be used on both sides of the mould as need be. Generally the polymers are kept separately and mixed in a nozzle before spraying. The process can be fully automated. Sandwich structures can also be produced.	Rovings. Polynol & Isocyanate (PUR) Additives. Surface finishes	Thin parts. Fast process. Higher production due to automation. Uniformity of fiber loading. Inclusion of inserts. Good surface finish. Generally low emissions due to closed moulds.	Additional equipment and precision mould costs. Limitation of part size due to pressure requirements.	Automotive Consumer goods Transportation. Electronic goods. Medical. Aerospace.

BULK MOULDING COMPOUND (BMC-) INJECTION and COMPRESSION MOULDING

Description	Natural fiber material & Matrix	Advantages	Disadvantages	Typical products/ markets
This is a two step process. BMC is produced by mixing the polymer with chopped fibers. In the 2nd process stage resin dough is moulded by compression moulding or injection moulding. The BMC doughy material is placed into a hopper that feeds the system. The dough is fed to the heated plasticizing section. Precise dosing and injection to mould. Part cures in mould.	BMC is reinforced with short fiber. Polyesters or Vinyl ester. Additives for improved interface bonding.	Pre-mixed compound. Complex parts. Higher production. Both surfaces could have good finish.	Limited storage of material. Costly equipment. Limitation of part size due to pressure requirements.	Electrical appliances. Small & large Automotive parts. Construction & Housing. Transportation.

SHEET MOULDING COMPOUND (SMC) COMPRESSION MOULDING

Description	Natural fiber material & Matrix	Advantages	Disadvantages	Typical products/ markets
This is a two step process. SMC is manufactured in 1st stage and supplied with long fibers chopped and dispersed in the resin. Resin paste is deposited to and covered by carrier films on both sides. The polymers are often highly loaded with additive. The resin paste is “thickened” to facilitate moulding. The sheets can be cut and the charge is about 70% area of mould size. Part produced by compression in heated moulds. The charge flows in the mould to final shape.	In SMC fiber lengths could be 20-50 mm. SMC supplied in 1-2 m rolls of 1-3mm thickness. Mostly Polyesters. Vinyl ester, epoxy also possible. Additives for improved interface bonding. SMC could also include oriented fibers.	Pre-mixed materials. Matched moulds & dimensional control. SMC has better properties compared to BMC due to longer fibers. Higher production. Large complex parts. Inserts and ribs.	Limited storage of material. Costly equipment. Operator skills	Automotive parts. auto body parts, doors etc. Construction & Housing. Transportation. Electrical component housing Sinks, baths etc. Consumer appliances housing Etc.

COMPRESSION MOULDING

Description	Natural fiber material & Matrix	Advantages	Disadvantages	Typical products/ markets
There are many variations to compression moulding. The technique can be combined with other processes. Polymer pre-impregnated non-woven mats produced and supplied in rolls or sheets. The mats are cut to size and placed in heated moulds. Then consolidated and cured with heat and pressure. Compressed parts can be laminated to desired surface finish.	Generally Non-woven Wide range of thermoplastic and Thermoset polymers can be used. Additives for improved interface bonding.	Complex parts. Narrow tolerances. Higher production. Uniformity of fiber loading. Good properties. Surfaces finishes possible. Inserts possible. Generally low emissions due to closed moulds.	Additional equipment and precision mould costs. Limitation of part size due to press size needed. Limited mould depth Some secondary processing e.g. trimming.	Automotive parts Furniture. Construction & Housing. Transportation sector. Consumer goods.

INJECTION MOULDING

Description	Natural fiber material & Matrix	Advantages	Disadvantages	Typical products/ markets
There are many variations and advancements in this technique. Natural fibers are compounded with the polymer in an extruder and formed to granules for further processing. The NF/polymer granules are fed to injection moulding equipment; The injection screws have specific length to diameter ratio. The screw consists mostly of a conveying section, a plasticizing sections and a pumping section. The plasticized material is injected into a closed mould held in a clamp mechanism. Mould held closed for a short period. Cooling period. Moulds opened and final parts are ejected. Properties of mix improved by additives.	Natural fiber & Thermoplastic matrix granulated. Additives for improved interface bonding.	Finish surface quality good. Complex parts. Narrow tolerances. High production volumes. Fast production. Consistent parts. Low cost. Generally low emissions due to closed moulds.	Equipment and precision mould costs. Limitation of part size due to pressure requirements. NF/Polymer granulation could be difficult.	Very wide range of product and market combinations.

DIRECT INJECTION MOULDING (Long Fiber Technique)

Description	Natural fiber material & Matrix	Advantages	Disadvantages	Typical products/ markets
There are many variations and advancements in injection moulding techniques. Natural fibers and the Thermoplastic matrix in mixed directly in the extruder. The plasticized NF/ polymer material is injected into a closed mould held in a clamp mechanism. Moulds opened and final part are ejected. Properties of mix improved by additives.	Natural fiber Thermoplastic matrix granulated. Additives for improved interface bonding.	Surface finish quality good. Complex parts. Narrow tolerances. Higher production. Generally low emissions due to closed moulds.	Equipment and precision mould costs. Limitation of part size due to pressure requirements.	Marine. Furniture. Construction & Housing. Tanks & Pools. Transportation. Prototype of moulds. Flat and structured sheets.

LONG FIBER TECHNOLOGY (LFT) AND DIRECT LONG FIBER TECHNOLOGY (D-LFT)

Description	Natural fiber material & Matrix	Advantages	Disadvantages	Typical products/ markets
The ideal concept would be to have one system to deal with material processes and end-part production on site. LFT-D is a partial solution to compression moulded parts. The plasticizing of the thermoplastic in an extruder and the mixing of long natural fibers (10-25) mm result in a dough. The dough is transferred immediately to a mould in a press. The dough compressed to desired shape. Part removed/ejected from mould.	Roving and yarns Generally Thermoplastic. Additives for improved interface bonding.	Control of fiber and matrix on site. Complex parts. Narrow tolerances. Higher production. Uniformity of fiber loading. Generally low emissions due to closed moulds.	Additional equipment and precision mould costs. Limitation of part size due to pressure requirements. Depth of mould. .	Automotive Transportation. Construction & Housing.

PULTRUSION

Description	Natural fiber material & Matrix	Advantages	Disadvantages	Typical products/ markets
A continuous process to produce linear profiles, rods, etc. NF rovings are taken through bath to impregnate with resin. The impregnated fibers are cured in heated die. The strands are then pulled through a die with the required profile. Cut to required profile length.	Natural Fiber yarns and rovings. Low cost NF wovens and nonwovens fabrics. Polyesters and vinyl esters. Epoxies possible. Thermoplastics has also been tried. Additives for improved interface bonding.	Very good surface properties. High fiber loading, up to 70%. Continuous process. Range of profiles and rods. Can be low cost and fast production rate.	Investment in equipment. Fiber architecture is generally unidirectional.	Consumer goods Furniture parts. Construction & Housing. Sporting & recreation. Typically profiles, rods, beams, panels etc.

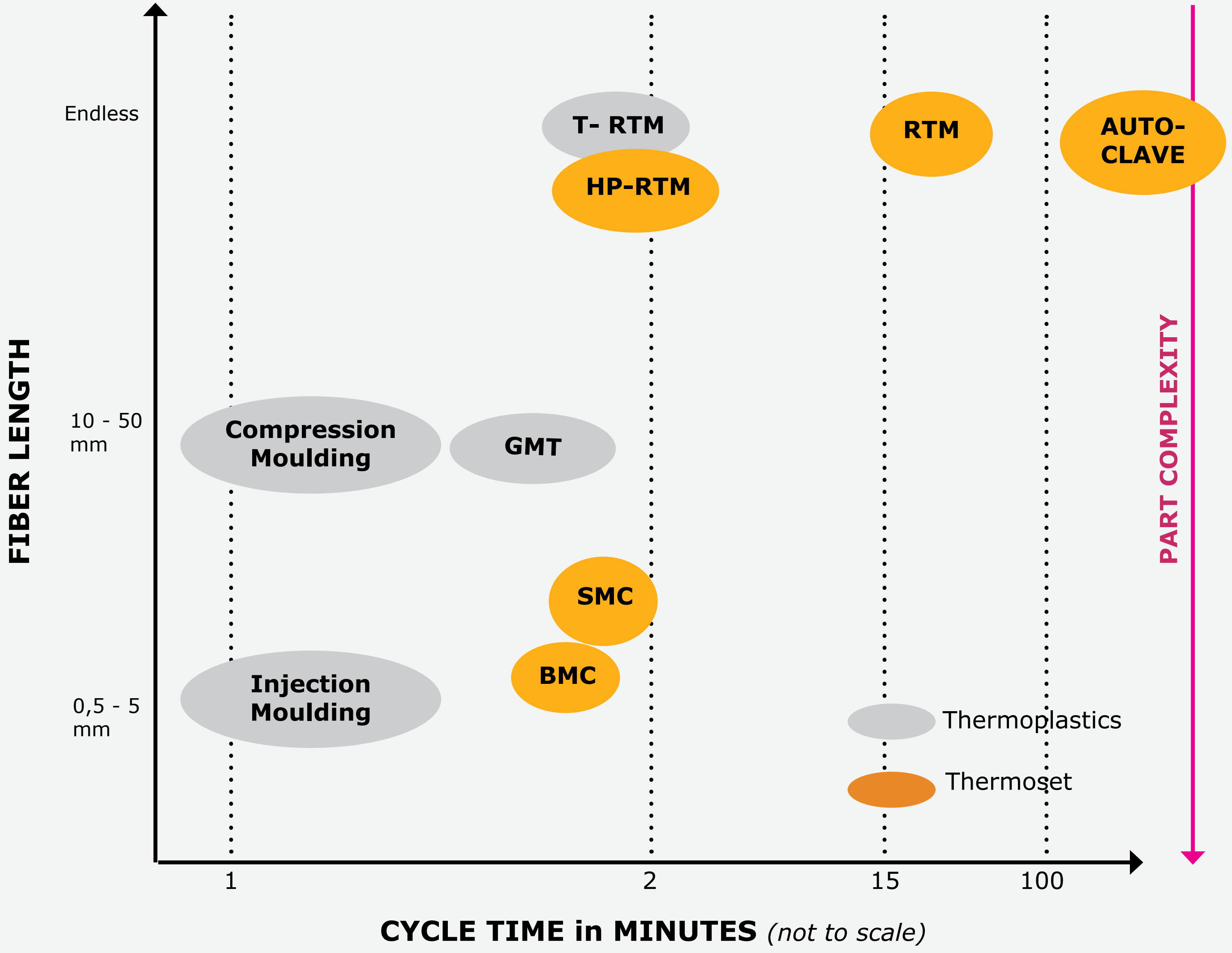
FILAMENT WINDING

Description	Natural fiber material & Matrix	Advantages	Disadvantages	Typical products/ markets
An open mould and automated process. Fiber yarns or tows pass through a resin bath to be wetted and wound around a mandrel with a desired form. The mandrel is the mould. Depending on the desired product several winding patterns can be used. End caps can be separately attached for vessels etc. Curing on mandrel by heat. Cure time of resin could be improved by additives like accelerators and catalysts.	NF yarns. Fabrics can be used for inner and outer finish. Polyesters & Epoxies. But polyesters or vinyl ester resins possible. Additives for improved interface bonding.	Good properties due to continuous fibers. Good reproducibility due to automated process. Large parts possible.	Investment in equipment. Removal of the mandrel at completion of process. Can be expensive tools.	Tanks, pipes & Vessels. Transportation. Consumer goods Sporting & recreation. Construction & Housing.

AUTOCLAVE

Description	Natural fiber material & Matrix	Advantages	Disadvantages	Typical products/ markets
Autoclave is a moulding method. Release agent is applied to the mould. Complemented by a Gel-Coat to improve the surface finish and aesthetic effect. Fabrics pre-impregnated with resins and partially cured are cut and placed into the moulds. Placement is mostly done by hand as in vacuum bagging. The number of layers of prepregs used depends on the desired part properties. Several layers of functional materials are used for optimal operations Finally covered by a vacuum bag. All edges are sealed to ensure no leakages and to maintain vacuum in the system.The air and emissions removed by vacuum system. Curing at in the autoclave with pressure and temperature. Curing can also be in special ovens or autoclave. Cure time of resin could be improved by additives like accelerators and catalysts.	Non-woven & Woven mats. Mostly Epoxies. Additives for improved interface bonding.	Can be used for complex and large size parts, depending on autoclave size. Inclusion of inserts. Very good properties. High fiber volume. Low emissions.	Labour intensive. Low production time. Investment in autoclave. Pre-Pregs can be expensive. Shelf life of prepregs.	Mostly Aircraft parts. Marine parts. Furniture. Construction & Housing. Transportation.

Typical composite process cycle time and fiber length at end of processing *(Not all composites technolgies are shown)*



Source: Thierry Renault, Faurecia Automotive Seating (2013)

Note: Depending on thermoset resin used curing time could take hours

APPENDIX 1

AN INTRODUCTION TO POLYMERS

(SOME TECHNICAL POINTS
FOR NONTECHNICAL READERS)

What is this appendix about?

In chapter 6 polymers and their application as polymer matrix in composites were introduced. The polymer matrix can be thermoplastics, thermosets or elastomers. These polymers are characterized according to their chemical properties and behaviour. Chapter 6 also introduced biobased materials including bioplastics. This appendix provides an initial technical introduction to polymers and plastics. There are several excellent books on this subject but this appendix can be a starting point.

Brief introduction to hydrocarbon and carbohydrate chemistry

Polymers and biobased materials could be better understood by understanding the different disciplines of chemistry, namely hydrocarbon chemistry and carbohydrate chemistry.

Hydrocarbons: The basis for fossil/petro based polymers

"In the early days" it was thought that "organic chemicals" were found only in living things. "Inorganic" chemicals (mostly minerals) were those found in non-living things. For a long time it was thought that chemicals had a life force within them, hence the use of the word organic. Inorganic chemicals did not have a life force.

The common feature of organic chemicals is that they all contain the element carbon. Carbon plays a central role in organic chemistry. Carbon is able to combine with other elements such as hydrogen, oxygen and nitrogen. It is believed that no other element is able to make a wide variety of chains like carbon. In 1828 Friedrick Wöhler, a German chemist, showed that urea, an organic compound found in urine, could be produced from an inorganic compound. The whole concept of life force in organic chemistry seems to have been displaced. The use of the term *organic chemistry* was officially attested around the year 1831. Organic Chemistry today is about the study of matter that contains carbon atoms and the compounds that could be made from them. The word "organic" as commonly used now started around 1942. It mainly refers to "free from pesticides and fertilizers". Implicitly organic materials refer to substances that would not harm life. Today the general use of the word "organic" is rather different to the meaning organic as used in chemistry. *In the modern context there is nothing organic about organic chemistry.*

According to the Oxford dictionary organic means:

i**n chemistry:** relating to or denoting compounds containing carbon (other than simple binary compounds and salts) and chiefly or ultimately of biological origin.

in food or farming methods: produced or involving production without the use of chemical fertilizers, pesticides, or other artificial chemicals.

Organic is characterized by a harmonious relationship between the elements as a whole; the organic unity of the integral work of art. Or characterized by gradual or natural development: the organic growth of community projects.

Hydrocarbons consist of a carbon backbone with hydrogen atoms joined to it. But it could have other atoms such as O, N, S, P, Si, B, Halogens and metals attached to them too. Many industries have emerged and are emerging based on hydrocarbon science, just to name a few, plastics, dyes, paints, food, agrochemicals, medicines for humans and animals. Chemists have devised ingenious ways to name the wide range of combinations or organic compounds.

Carbohydrates: The basis for biobased polymers

Carbohydrates are substances that contain only three elements, namely carbon, hydrogen and oxygen. Carbohydrates means the Hydrates of Carbon; written $C_n(H_2O)_n$.

Carbohydrates play an important part in "living things". They are central to natural fibers and the production of bioplastics. Carbohydrates store chemical energy. They are formed by photosynthesis. In this process green plants and algae for example use the energy from the sun to convert carbon dioxide and water into glucose (simple sugars) and oxygen. The oxidation of glucose forms carbon dioxide, water and lots of energy.
For example sugars are simple carbohydrates, with the ability to link together to make polymers such as starch and cellulose. These are polymer chains with great length, *Polysaccharides.* In plain English it means "many-sugars" (Latin word for sugars is *saccharum*). *Monosaccharides* are simple sugars. Glucose is the most common simple sugar. Generally three or more monosaccharides join together to form a polysaccharide.

Cellulose is the most common carbohydrate, as polysaccharide, of the plant world e.g. it is the basis for wood, fibers, grasses etc. Cellulose is found in the cell walls of nearly all plants. Cellulose plays a very important role in natural fibers.

Cotton is a pure carbohydrate cellulose polymer. Whereas natural fibers such as jute, abaca, coir, kenaf, sisal, flax and hemp have varying amounts of cellulose. These are natural materials. However, *regenerated* (made) fibers of cellulose, e.g. *cellulose acetate* or *cellulose nitrates*, are produced too. Is it still cellulose?

Cellulose has a structure that has exceptional strength and provides support to plants. For various reasons, cellulose is water insoluble. Nature has made cellulose such that this important polymer does not dissolve in water and hence makes the supporting structure weak and collapse. The exceptional mechanical properties of cellulose make it an interesting material for use in products; also in *nanomaterial* products.

Starch is a carbohydrate that is in roots and seeds of plants. Examples are potato, rice, corn and wheat. Unlike cellulose, starch is water soluble.
The water solubility of starch can be problematic when it is used as a binder in composite applications.

POLYMERS AND PLASTICS

Long before synthetic materials were produced man used natural materials. This included natural polymers too. They were mainly derived from bones, horns, the sap of various trees (amber), waxes etc. Many such materials are used even today. Natural polymers were used in many cultures and ancient civilizations to produce very fine artefacts for products for everyday use. Even fully biobased composite products were made in the past.

For example 100 years ago or so biocomposite products such as *shellac* gramophone records and medallions of *Bois Durci* were produced. The gramophone record was made from shellac, cotton fiber and mineral additives. Bois Durci consisted of a protein - animal blood from the slaughter houses of Paris - wood filler and colour pigments.

In this period materials such as ivory and tortoise shell, were getting difficult to obtain. This triggered the search for alternatives and people started to experiment with materials. The early plastics were modifications of natural polymers. Only with the development of organic chemistry did large scale production of synthetic or man-made polymers become fully industrialized. These developments enabled "ordinary citizens" to purchase products and this could be considered the early days of mass consumption in the modern context.

Fred Gaisberg (who was working in 1900 for Emile Berliner,) who is credited with invention of the flat records *shellac,* a material used for making buttons in a factory in Newark, New Jersey. Berliner started to use the material to make 78 rpm flat discs, the surface was laced with slate to wear down the needles, instead of the needles wearing down the disc.
Source:www.jiscdigitalmedia.ac.uk
http://www.emil-berliner-studios.com/en/chronik1.html

Bois Durci is a natural polymer based composite made in 1856 in Paris by Francois Charles Lepage, consisting of animal blood filled with wood dust and colouring. The mix was heat moulded under pressure to obtain a hard, dense, glossy wood like material. In Paris Lepage produced several desk items such as inkwell stands and plaques. Production ended sometime around 1920.
Medallions Pope Pius IX. Bois Durci, 1870, Dm. 11 cm
Accessed 24 Dec 2014. http://de.wikipedia.org/wiki/Bois_Durci

It is claimed that Charles Goodyear laid the foundation for producing semi-synthetic polymers. He heated a natural polymer i.e. latex rubber and sulphur together to form a hard material, he called it *Vulcanite.*
However historians say that even around 1000 BC, the Indians in South America used the natural latex rubber and sulphur rich plants to produce stabilized or vulcanized latex rubber to make products such as balls and hoses. The South American Indians lost control of the latex rubber trade. Goodyear never made any fortune from his inventions.

From 1850 onwards polymers such as *cellulose nitrate* (invented by John Wesley Hyatt of USA) and Parkesine (invented in 1868 by Alexander Parks of UK) arise. *Celluloid* is the first semi-synthetic commercially successful thermoplastic material.

Vulcanite Match-Box 1880

Celluloid products 1910

Source: Science Museum London

Some basic terminology of polymers

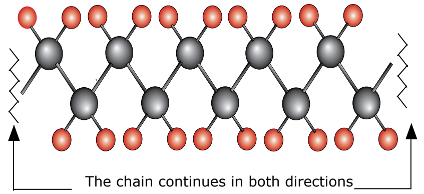
Essentially “poly” means many and “mer” means units. Polymer means many units. Mono-mer, di-mer etc, refer to the units. Polymers are organic carbon based compounds chemists would say. They are composed of large molecules, with high relative molecular mass of repeating smaller units linked into long chains. The smaller units are called monomers, which are bonded covalently to form polymers. Polymers are often called *macromolecules* because they are very long molecules formed by joining many thousands of small units of monomers in a process called *polymerization*. *Polyethylene* is formed by polymerizing *ethylene* molecules.

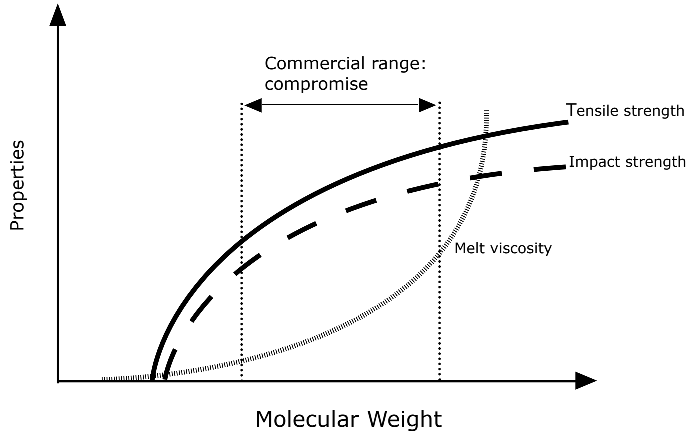
In the context of plastics, polymers are synthetic or artificial materials. The types of monomers and linkages can be manipulated to produce a wide range of materials with properties such as strength, flexibility, density, transparency, chemical stability etc. Essentially the differences in polymers can be due to the type of monomers used and how the polymer chains interact or are bonded together.
The building blocks, i.e. monomers, are referred to as organic molecules based on carbon. The building blocks are mainly derived from *petroleum (oil),* natural gas or sugars. Generally polymers are based on hydrocarbons. But polymers can also be from other natural or from plant material such as rubber, cotton, wood, banana peel, corn or from animal origins such as silk or wool or other real “organic” materials such as tortoise shell, bones, etc.

From a structural view point, the most important properties of polymers are determined by:

- the rigidity of the polymer molecules.
- attracting forces between the chains.
- the crystalline domains i.e. the degree to which the chains form them.
- the degree of cross-linking between the chains.

Polyethylene - CH_2





With increasing molecular weight tensile and impact strength increases rapidly then levels off. The melt viscosity continues to increase.
BUT even though the strength increases with high molecular weight these polymers are difficult to process due to high melt viscosity.
In commercial production of polymers there is a compromise between properties and processability. The same polymer could exhibit a range of molecular weight and complicate matters!

When polymers are produced they could have a neat structure of parallel chains. This does not mean that the chains are neatly in a straight line, but the carbon atoms form a zig-zag pattern. The molecular chains can bend, coil and kink. Chains can become entangled as well. The parts of the polymers where the chains are ordered are the *Crystalline regions.* The chains can be disorderly and be at random in the *Amorphous regions.* Polymers are hardly fully ordered chains but a mix of crystalline, *micro-crystalline* and amorphous regions. They generally have all these domains but which structure dominates depends greatly on the molecular arrangements, chemical composition and how they were processed. Crystalline polymers tend to be strong and stiff (e.g. *Polythene, Nylon* etc.).

When the chains are tangled and are in disorder, the polymer is amorphous or shapeless. Polymers with high crystalline structure could be brittle; while amorphous regions tend to provide toughness, meaning they can bend without breaking. Amorphous polymers are less dense than crystalline polymers. They tend to be transparent. This is an important characteristic for many applications such as *Plexiglas*, headlights and contact lenses.

High crystallinity of a polymer means higher density, more strength, higher resistance to dissolution and softening by heat. The higher the degree of crystallinity, the less light can pass through the polymer. Therefore, translucent to opaqueness is directly effected by the crystallinity of the polymer. Something product designers should take into consideration.

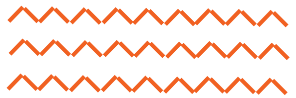
The polymers could have different structural configuration:

Linear polymers: long chain of monomers. The polymer chains are close to each other but do not chemically combine. They can be packed tightly and be flexible. Example Polyethylene, Nylon.

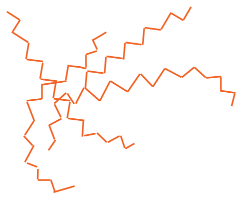
Branched polymer: the polymer has branches at irregular intervals. The branches make it difficult for the polymer to pack together hence are less crystalline and less dense.

Crossed linked polymers: the chains are covalently bonded with other chains. This is often achieved by adding atoms or molecules that form the covalent links between the chains. The links could be loosely crossed linked such as in rubber. In thermoset polymers, like epoxy, the cross-links are dense. They can be both crystalline and amorphous.

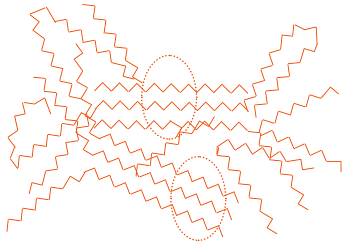
Network polymers: 3-dimensional networks of trifunctional mers. Network polymers are almost fully amorphous. Examples: *Epoxies, Phenolformaldehyde.*



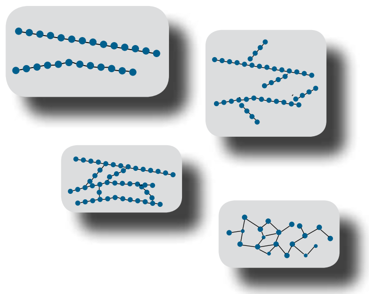
More orderly but less likely arrangement of polymer chain



More disorderly but more likely arrangement of polymer chain



Microcrystalline regions.
The chains are arranged with some areas packed with microcrystaline areas and other areas with chains arranged randomly.



There are other phenomena of polymers such as *folding, stacking and a sort of "wondering"* of the chains which will not be addressed in this chapter. The interested reader can refer to several books on polymer chemistry.

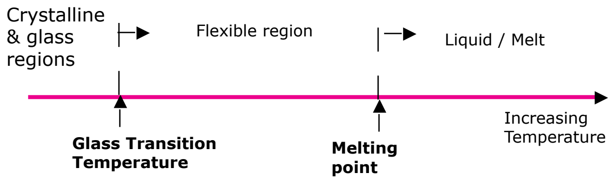
Crystalline and amorphous polymers react differently when subjected to heat. When the polymer is heated it will become soft and flexible. The temperature at this point is the *Glass Transition Temperature (*Normally written as Tg*)*. After this point the behaviour of crystalline and amorphous polymers are different. Crystalline polymers have a definite *melting point.* However, amorphous polymers behave differently to heat - they do not have a definite melting point but a glass transition only. Mostly crystalline polymers will also have amorphous regions. This means such a polymer would have both a glass transition temperature and a melting point.

The difference between melting and glass transition needs to be understood to avoid misunderstandings. Melting occurs in crystalline polymers. Glass transition in amorphous polymers or state.

At low temperature i.e. below the glass transition temperature, both polymers exhibit glassy behaviour. In this condition the materials would crack and shatter if hit hard. The reason for this type of damage is because the chains cannot easily move. They cannot absorb the energy of the hit. The energy goes to breaking the links between the chains or even the links in the chain itself. The chains can be cross-linked. A key characteristic of cross-links is the formation of strong bonds between the chains. Once the cross links are established they will not change even when heated, other than break-down, also in chemical composition.

Amorphous polymers

Crystalline polymers



Generally crossed-linked polymers are called "thermoset" polymers. Thermoplastic polymers have relatively weak links between the chains. They tend to soften when heated and hence can be remoulded. Elastomers could be subjected to forces and they would generally return to the original state. The chains may flex and twist. Sometimes additional substances, like *plasticisers* are used to enhance and improve the properties of elastomeric polymers. The crystallinity and the elastomeric properties of polymers can be controlled by the length of the polymer chains and the extent of branching (i.e. cross linking). The length of the chain (and material) will also influence the strength of the polymer.

The mechanical properties can also be influenced by adding substances such as *plasticisers, fillers or fibers*. Other properties such as *photodecomposition* (e.g. discoloration of paints by sunlight) could also be modified by addition of *stabilisers.* However it must be noted that due to certain requirements the polymers could be designed so that they decompose when subjected to light or left in contact with air over a certain amount of time. This phenomena is not *biodegradation* but *decomposition*. In chapter 6 of this book biodegradation, fragmentation and composting are discussed.

Copolymers

Copolymers have at least two different types of mers (or units). In *Homopolymer* the monomers are of the same type. However they can have different monomers and the arrangement can differ.

The different types of copolymers are:

- *Random copolymer:* two or more differently repeating units but distributed randomly.
- *Alternating copolymers:* alternating sequence of different monomers.
- *Block copolymer:* long sequences of a monomer followed by a long sequence of another monomer.
- *Graft copolymer:* a chain of one monomer with branches of another type of monomer.

Behaviour of and failure of polymers

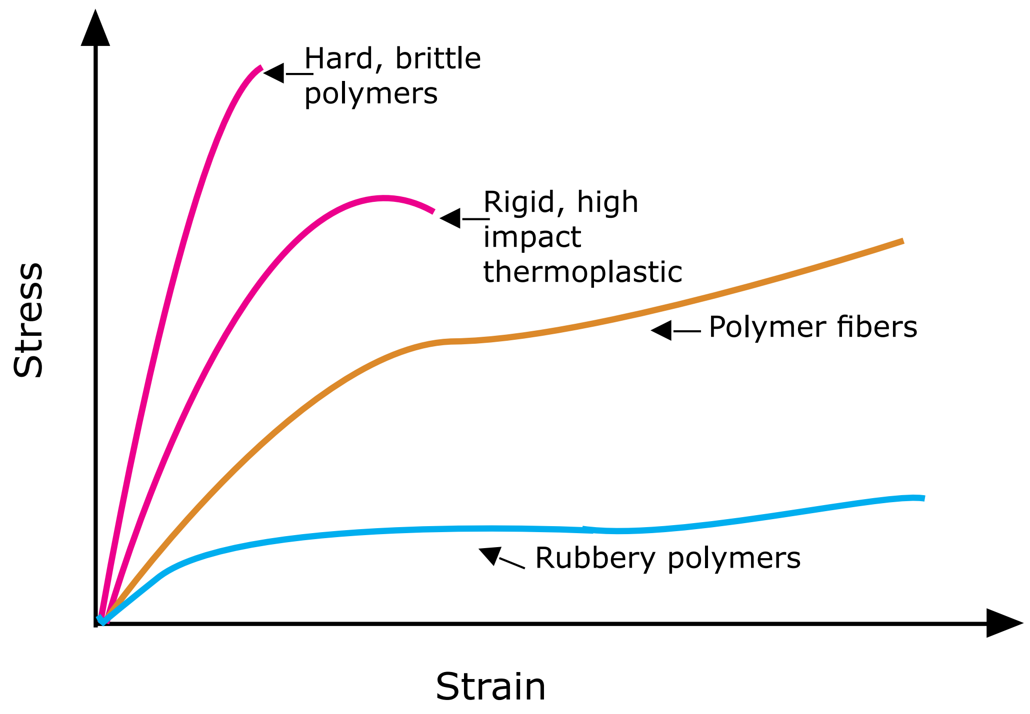
If a polymer is subjected to a force it will deform and ultimately fail. How the material will behave depends on the type of polymer. As a general illustration the *stress-strain* behaviour for different polymer types is shown in figure A1. The theory of polymer under stress and strain will not be discussed further.

Figure A1: The behaviour of different types of polymers under (tensile) load

Stress: A force applied to the sample.

Strain: As the force increases the sample stretches. The measure of stretch is the called the strain.

The end points of the graph are where the sample breaks



Design consideration: Perception of plastic products - homogeneity versus diversity of nature

How “the plastics industry” displaced many natural materials and how the industry influenced, changed humans perception of aesthetics and appreciation of materials is a fascinating subject, also for product designers of different schools. Unfortunately this subject is beyond the scope of this book. One single point that stands out in the matter is how the general public, including product designers, has been led to believe in the “unnatural homogeneity” created by the chemists in plastics as being a very desirable characteristic of products. It would not be an exaggeration to say that from an aesthetic view point this may have even defined the perception of perfection.

While homogeneity of some plastics is considered perfect, the diversity and natural character of “disorderliness” are often considered undesirable. For example in the early days when “Formica” tables were introduced to the markets, many felt it a “cheap” material more suitable for “unsophisticated” people. Even people we characterised as “plastic” when their appearance and behaviour was “fake”. With successful marketing by the plastics industry the perception was changed. As a result in some instances natural products were disliked for their “imperfections”. Something for product designers to ponder upon.

The key challenge for designers wishing to work with natural materials such as fibers is to incorporate the diversity, also in terms of properties, these materials naturally have in the product design.

APPENDIX 2

BUZZ WORDS:
COMPOSITES
&
NATURAL FIBERS

(SOME COMMONLY USED
TECHNICAL TERMS.
NOT LIMITATIVE)

> The menu
> is not
> the meal.
>
> Alan Wilson

GLOSSARY OF TERMS: COMPOSITES (Not limitative)

This glossary of terms has been simplified as an introduction to commonly used composites industry terms. The original version has been compiled from the Composite Material Handbook (MIL-HDBK-17), published by the US Department of Defence (2002).

Absorption: A process in which one material (the absorbent) takes in or absorbs another (the absorbate).

Accelerator: A material which, when mixed with a catalyzed resin, will speed up the chemical reaction between the catalyst and the resin.

Adhesion: The state in which two surfaces are held together at an interface by forces or interlocking action or both.

Anisotropic: Not isotropic; having mechanical and/or physical properties which vary with direction relative to natural reference axes inherent in the material.

Areal Weight of Fiber: The weight of fiber per unit area of prepreg. This is often expressed as grams per square meter.

Autoclave Molding: A process similar to the pressure bag technique. The lay-up is covered by a pressure bag, and the entire assembly is placed in an autoclave capable of providing heat and pressure for curing the part. The pressure bag is normally vented to the outside.

Bag Molding: A method of molding or laminating which involves the application of fluid pressure to a flexible material which transmits the pressure to the material being molded or bonded. Fluid pressure usually is applied by means of air, steam, water or vacuum.

Balanced Laminate: A composite laminate in which all laminae at angles other than 0 degrees and 90 degrees occur only in ± pairs (not necessarily adjacent).

Bearing Load: A compressive load on an interface.

Bearing Yield Strength: The bearing stress at which a material exhibits a specified limiting deviation from the proportionality of bearing stress to bearing strain.

Bend Test: A test of ductility by bending or folding, usually with steadily applied forces. In some instances the test may involve blows to a specimen having a cross section that is essentially uniform over a length several times as great as the largest dimension of the cross section.

Bleeder Cloth: A nonstructural layer of material used in the manufacture of composite parts to allow the escape of excess gas and resin during cure. The bleeder cloth is removed after the curing process and is not part of the final composite.

Braid: A system of three or more yarns which are interwoven in such a way that no two yarns are twisted around each other.

Braid Angle: The acute angle measured from the axis of braiding.

Braid, Two-Dimensional: Braided fabric with no braiding yarns in the through thickness direction.

Braid, Three-Dimensional: Braided fabric with one or more braiding yarns in the through thickness direction.

Braid, Triaxial: A biaxial braided fabric with laid in yarns running in the axis of braiding.

Braiding: A textile process where two or more strands, yarns or tapes are intertwined in the bias direction to form an integrated structure.

Buckling (Composite): A mode of structural response characterized by an out-of-plane material deflection due to compressive action on the structural element involved. In advanced composites, buckling may take the form not only of conventional general instability and local instability but also a micro-instability of individual fibers.

Bundle: A general term for a collection of essentially parallel filaments or fibers.

Caul Plates: Smooth metal plates, free of surface defects, the same size and shape as a composite lay- up, used immediately in contact with the lay-up during the curing process to transmit normal pressure and to provide a smooth surface on the finished laminate.

Chain-Growth Polymerization: One of the two principal polymerization mechanisms. In chain-growth polymerization, the reactive groups are continuously regenerated during the growth process. Once started, the polymer molecule grows rapidly by a chain of reactions emanating from a particular reactive initiator which may be a free radical, cation or anion.

Cocuring: The act of curing a composite laminate and simultaneously bonding it to some other prepared surface during the same cure cycle (see Secondary Bonding).

Composite Material: Composites are considered to be combinations of materials differing in composition or form on a macroscale. The constituents retain their identities in the composite; that is, they do not dissolve or otherwise merge completely into each other although they act in concert. Normally, the components can be physically identified and exhibit an interface between one another.

Compound: An intimate mixture of polymer or polymers with all the materials necessary for the finished product.

Condensation Polymerization: This is a special type of step-growth polymerization characterized by the formation of water or other simple molecules during the stepwise addition of reactive groups.

Continuous Filament: A yarn or strand in which the individual filaments are substantially the same length as the strand.

Crazing: Apparent fine cracks at or under the surface of an organic matrix. Creep -- The time dependent part of strain resulting from an applied stress. Creep, Rate Of -- The slope of the creep-time curve at a given time.

Crossply: Any filamentary laminate which is not uniaxial. Same as Angleply. In some references, the term crossply is used to designate only those laminates in which the laminae are at right angles to one another, while the term angle ply is used for all others.

Cure: To change the properties of a thermosetting resin irreversibly by chemical reaction, i.e., condensation, ring closure, or addition. Cure may be accomplished by addition of curing (cross-linking) agents, with or without catalyst, and with or without heat. Cure may occur also by addition, such as occurs with anhydride cures for epoxy resin systems.

Cure Cycle: The schedule of time periods at specified conditions to which a reacting thermosetting material is subjected in order to reach a specified property level.

Cure Stress: A residual internal stress produced during the curing cycle of composite structures. Normally, these stresses originate when different components of a lay-up have different thermal coefficients of expansion.

Debond: A deliberate separation of a bonded joint or interface, usually for repair or rework purposes.

Deformation: The change in shape of a specimen caused by the application of a load or force.

Degradation: A deleterious change in chemical structure, physical properties or appearance.

Delamination: The separation of the layers of material in a laminate. This may be local or may cover a large area of the laminate. It may occur at any time in the cure or subsequent life of the laminate and may arise from a wide variety of causes.

Desorption: A process in which an absorbed or adsorbed material is released from another material. Desorption is the reverse of absorption, adsorption, or both.

Disbond: An area within a bonded interface between two adherends in which an adhesion failure or separation has occurred. It may occur at any time during the life of the structure and may arise from a wide variety of causes. Also, colloquially, an area of separation between two laminae in the finished laminate (in this case the term "delamination" is normally preferred.)

Ductility: The ability of a material to deform plastically before fracturing.

Elasticity: The property of a material which allows it to recover its original size and shape immediately after removal of the force causing deformation.

Elongation: The increase in gage length or extension of a specimen during a tension test, usually expressed as a percentage of the original gage length.

End: A single fiber, strand, roving or yarn being or already incorporated into a product. An end may be an individual warp yarn or cord in a woven fabric.

Epoxy Equivalent Weight: The number of grams of resin which contain one chemical equivalent of the epoxy group.

Epoxy Resin: Resins which may be of widely different structures but are characterized by the presence of the epoxy group. The aromatic type epoxy resins are normally used in composites.

Fabric, Nonwoven: A textile structure produced by bonding or interlocking of fibers, or both, accomplished by mechanical, chemical, thermal, or solvent means, and combinations thereof.

Fabric, Woven: A generic material construction consisting of interlaced yarns or fibers, usually a planar structure. Specifically, a cloth woven in an established weave pattern from advanced fiber yarns and used as the fibrous constituent in an advanced composite lamina. In a fabric lamina, the warp direction is considered the longitudinal direction, analogous to the filament direction in a filamentary lamina.

Fiber: A general term used to refer to filamentary materials.

Fiber Content: The amount of fiber present in a composite. This is usually expressed as a percentage volume fraction or weight fraction of the composite.

Fiber Count: The number of fibers per unit width of ply present in a specified section of a composite.

Fiber Direction: The orientation or alignment of the longitudinal axis of the fiber with respect to a stated reference axis.

Fiber System: The type and arrangement of fibrous material which comprises the fiber constituent of an advanced composite. Examples of fiber systems are collimated filaments or filament yarns, woven fabric, randomly oriented short-fiber ribbons, random fiber mats, whiskers, etc.

Filament (man made): The smallest unit of a fibrous material. The basic units formed during spinning and which are gathered into strands of fiber, (for use in composites). Filaments usually are of extreme length and of very small diameter. Filaments normally are not used individually. Some textile filaments can function as a yarn when they are of sufficient strength and flexibility.

Filamentary Composites: A major form of advanced composites in which the fiber constituent consists of continuous filaments. Specifically, a filamentary composite is a laminate comprised of a number of laminae, each of which consists of a nonwoven, parallel, uniaxial, planar array of filaments (or filament yarns) embedded in the selected matrix material. Individual laminae are directionally oriented and combined into specific multiaxial laminates for application to specific envelopes of strength and stiffness requirements.

Filament Winding: A reinforced-plastics process that employs a series of continuous, resin- impregnated fibers applied to a mandrel in a predetermined geometrical relationship under controlled tension.

Fill (Filling)/Weft: In a woven fabric, the yarn running from selvage to selvage at right angles to the warp.

Filler: A relatively inert substance added to a material to alter its physical, mechanical, thermal, electrical, and other properties or to lower cost. Sometimes the term is used specifically to mean particulate additives.

Finish (or Size System): A material, with which filaments are treated, which contains a coupling agent to improve the bond between the filament surface and the resin matrix in a composite material. In addition, finishes often contain ingredients which provide lubricity to the filament surface, preventing abrasive damage during handling, and a binder which promotes strand integrity and facilitates packing of the filaments.

Flash: Excess material which forms at the parting line of a mold or die, or which is extruded from a closed mold.

Fracture Ductility: The true plastic strain at fracture.

Gel: The initial jelly-like solid phase that develops during formation of a resin from a liquid. Also, a semi-solid system consisting of a network of solid aggregates in which liquid is held.

Gel Coat: A quick-setting resin used in molding processes to provide an improved surface for the composite; it is the first resin applied to the mold after the mold-release agent.

Gel Point: The stage at which a liquid begins to exhibit pseudo-elastic properties. (This can be seen from the inflection point on a viscosity-time plot.)

Gel Time: The period of time from a pre-determined starting point to the onset of gelation (gel point) as defined by a specific test method.

Glass Transition: The reversible change in an amorphous polymer or in amorphous regions of a partially crystalline polymer from (or to) a viscous or rubbery condition to (or from) a hard and relatively brittle one.

Glass Transition Temperature: The approximate midpoint of the temperature range over which the glass transition takes place.

Hand Lay-up: A process in which components are applied either to a mold or a working surface, and the successive plies are built up and worked by hand.

Horizontal Shear: Sometimes used to indicate interlaminar shear.

Hybrid: A composite laminate comprised of laminae of two or more composite material systems. Or, a combination of two or more different fibers such as natural fiber and glass or carbon into a structure (tapes, fabrics and other forms may be combined).

Impact: It is the resistance to fracture when certain localized load is applied to the specimen. The two types are Notched and Unnotched.

Inclusion: A physical and mechanical discontinuity occurring within a material or part, usually consisting of solid, encapsulated foreign material. Inclusions are often capable of transmitting some structural stresses and energy fields, but in a noticeably different manner from the parent material.

Interface: The boundary between the individual, physically distinguishable constituents of a composite. Interlaminar: Descriptive term pertaining to some object (e.g., voids), event (e.g., fracture), or potential field (e.g., shear stress) referenced as existing or occurring between two or more adjacent laminae.

Intralaminar: Descriptive term pertaining to some object (e.g., voids), event (e.g., fracture), or potential field (e.g., temperature gradient) existing entirely within a single lamina without reference to any adjacent laminae.

Isotropic: Having uniform properties in all directions. The measured properties of an isotropic material are independent of the axis of testing.

Knitting: A method of constructing fabric by interlocking series of loops of one or more yarns.

Lamina: A single ply or layer in a laminate made up of a series of layers.

Laminae: Plural of lamina.

Laminate: A product made by bonding together two or more layers or laminae of material or materials.

Laminate Orientation: The configuration of a cross plied composite laminate with regard to the angles of crossplying, the number of laminae at each angle, and the exact sequence of the lamina lay-up.

Lay-up: A process of fabrication involving the assembly of successive layers of resin-impregnated material.

Mandrel: A form fixture or male mold used for the base in the production of a part by lay-up, filament winding or braiding.

Mat: A fibrous material consisting of randomly oriented chopped or swirled filaments loosely held together with a binder.

Matrix: The essentially homogeneous material in which the fiber system of a composite is embedded.

Modulus, Chord: The slope of the chord drawn between any two specified points on the stress-strain curve.

Modulus, initial: The slope of the initial straight portion of a stress-strain curve.

Modulus, Young's: The ratio of change in stress to change in strain below the elastic limit of a material. (Applicable to tension and compression).

Moisture Content: The amount of moisture in a material determined under prescribed condition and expressed as a percentage of the mass of the moist specimen, i.e., the mass of the dry substance plus the moisture present.

Moisture Equilibrium: The condition reached by a sample when it no longer takes up moisture from, or gives up moisture to, the surrounding environment.

Mold Release Agent: A lubricant applied to mold surfaces to facilitate release of the molded article.

Molded Edge: An edge which is not physically altered after molding for use in final form and particularly one which does not have fiber ends along its length.

Molding: The forming of a polymer or composite into a solid mass of prescribed shape and size by the application of pressure and heat.

Monolayer: The basic laminate unit from which crossplied or other laminates are constructed.

Monomer: A compound consisting of molecules each of which can provide one or more constitutional units.

NDE: Nondestructive evaluation. Broadly considered synonymous with NDI.

NDI: Nondestructive inspection. A process or procedure for determining the quality or characteristics of a material, part, or assembly without permanently altering the subject or its properties.

Oligomer: A polymer consisting of only a few monomer units such as a dimer, trimer, etc., or their mixtures.

Orthotropic: Having three mutually perpendicular planes of elastic symmetry.

Oven Dry: The condition of a material that has been heated under prescribed conditions of temperature and humidity until there is no further significant change in its mass.

Peel Ply: A layer of resin free material used to protect a laminate for later secondary bonding.

Plastic: A material that contains one or more organic polymers of large molecular weight, is solid in its finished state, and, at some state in its manufacture or processing into finished articles, can be shaped by flow.

Plasticizer: A material of lower molecular weight added to a polymer to separate the molecular chains. This results in a depression of the glass transition temperature, reduced stiffness and brittleness, and improved processability. (Note, many polymeric materials do not need a plasticizer.)

Polymer: An organic material composed of molecules characterized by the repetition of one or more types of monomeric units.

Polymerization: A chemical reaction in which the molecules of monomers are linked together to form polymers via two principal reaction mechanisms. Addition polymerizations proceed by chain growth and most condensation polymerizations through step growth.

Porosity: A condition of trapped pockets of air, gas, or vacuum within a solid material, usually expressed as a percentage of the total nonsolid volume to the total volume (solid plus nonsolid) of a unit quantity of material.

Post cure: Additional elevated temperature cure, usually without pressure, to increase the glass transition temperature, to improve final properties, or to complete the cure.

Pot Life: The period of time during which a reacting thermosetting composition remains suitable for its intended processing after mixing with a reaction initiating agent.

Preform: An assembly of dry fabric and fibers which has been prepared for one of several different wet resin injection processes. A preform may be stitched or stabilized in some other way to hold its shape. A commingled preform may contain thermoplastic fibers and may be consolidated by elevated temperature and pressure without resin injection.

Preply: Layers of prepreg material, which have been assembled according to a user specified stacking sequence.

Prepreg: Ready to mold or cure material in sheet form which may be tow, tape, cloth, or mat impregnated with resin. It may be stored before use.

Quasi-Isotropic Laminate: A laminate approximating isotropy by orientation of plies in several or more directions.

Release Agent: See Mold Release Agent.

Resilience: A property of a material which is able to do work against restraining forces during return from a deformed condition.

Resin: An organic polymer or prepolymer used as a matrix to contain the fibrous reinforcement in a composite material or as an adhesive. This organic matrix may be a thermoset or a thermoplastic, and may contain a wide variety of components or additives to influence; handleability, processing behavior and ultimate properties.

Resin Content: The amount of matrix present in a composite either by percent weight or percent volume.

Resin Starved Area: Area of composite part where the resin has a non-continuous smooth coverage of the fiber.

Resin System: A mixture of resin, with ingredients such as catalyst, initiator, diluents, etc. Required for the intended processing and final product.

Roving: A number of strands, tows, or ends collected into a parallel bundle with little or no twist. In spun yarn production, an intermediate state between sliver and yarn.

Sandwich Construction: A structural panel concept consisting in its simplest form of two relatively thin, parallel sheets of structural material bonded to, and separated by, a relatively thick, light-weight core.

Saturation: An equilibrium condition in which the net rate of absorption under prescribed conditions falls essentially to zero.

Scrim (also called Glass Cloth, Carrier): A low cost fabric woven into an open mesh construction, used in the processing of tape or other B-stage material to facilitate handling.

Secondary Bonding: The joining together, by the process of adhesive bonding, of two or more already-cured composite parts, during which the only chemical or thermal reaction occurring is the curing of the adhesive itself.

Selvage or Selvedge: The woven edge portion of a fabric parallel to the warp.

Shelf Life: The length of time a material, substance, product, or reagent can be stored under specified environmental conditions and continue to meet all applicable specification requirements and/or remain suitable for its intended function.

Size System: See Finish.

Sizing: A generic term for compounds which are applied to yarns to bind the fiber together and stiffen the yarn to provide abrasion-resistance during weaving. Starch, gelatin, oil, wax, and man-made polymers such as polyvinyl alcohol, polystyrene, polyacrylic acid, and polyacetatates are employed.

Sleeving: A common name for tubular braided fabric.

Staple: Either naturally occurring fibers or lengths cut from filaments.

Strain: the per unit change, due to force, in the size or shape of a body referred to its original size or shape. Strain is a nondimensional quantity, but it is frequently expressed in inches per inch, meters per meter, or percent.

Strand: Normally an untwisted bundle or assembly of continuous filaments used as a unit, including slivers, tow, ends, yarn, etc. Sometimes a single fiber or filament is called a strand.

Strength: the maximum stress which a material is capable of sustaining.

Stress: The intensity at a point in a body of the forces or components of forces that act on a given plane through the point. Stress is expressed in force per unit area (pounds-force per square inch, megapascals, etc.).

Stress-Strain Curve (Diagram): A graphical representation showing the relationship between the change in dimension of the specimen in the direction of the externally applied stress and the magnitude of the applied stress. Values of stress usually are plotted as ordinates (vertically) and strain values as abscissa (horizontally).

Surfacing Mat: A thin mat of fine fibers used primarily to produce a smooth surface on an organic matrix composite.

Symmetrical Laminate: A composite laminate in which the sequence of plies below the laminate midplane is a mirror image of the stacking sequence above the midplane.

Tack: Stickiness of the prepreg.

Tape: Prepreg fabricated in widths up to approx. 300 mm wide for carbon and approx. 75 mm for boron. Cross stitched carbon tapes up to 1500 mm wide are available commercially in some cases.

Thermoplastic: A plastic that repeatedly can be softened by heating and hardened by cooling through a temperature range characteristic of the plastic, and when in the softened stage, can be shaped by flow into articles by molding or extrusion.

Thermoset: A plastic that is substantially infusible and insoluble after having been cured by heat or other means.

Toughness: A measure of a material’s ability to absorb work, or the actual work per unit volume or unit mass of material that is required to rupture it. Toughness is proportional to the area under the load- elongation curve from the origin to the breaking point.

Tow: An untwisted bundle of continuous filaments. Commonly used in referring to man-made fibers, particularly carbon and graphite fibers, in the composites industry.

Transversely Isotropic: Descriptive term for a material exhibiting a special case of orthotropy in which properties are identical in two orthotropic dimensions, but not the third; having identical properties in both transverse directions but not the longitudinal direction.

Unbond: An area within a bonded interface between two adherends in which the intended bonding action failed to take place. Also used to denote specific areas deliberately prevented from bonding in order to simulate a defective bond, such as in the generation of quality standards specimens.

Unidirectional Laminate: A laminate with nonwoven reinforcements and all layers laid up in the same direction.

Vacuum Bag Molding: A process in which the lay-up is cured under pressure generated by drawing a vacuum in the space between the lay-up and a flexible sheet placed over it and sealed at the edges.

Void: A physical and mechanical discontinuity occurring within a material or part which may be two-dimensional (e.g., disbonds, delaminations) or three-dimensional (e.g. vacuum-, air-, or gas-filled pockets). Porosity is an aggregation of micro-voids. Voids are essentially incapable of transmitting structural stresses or nonradiative energy fields. (See Inclusion.).

Warp: The longitudinally oriented yarn in a woven fabric (see Fill); a group of yarns in long lengths and approximately parallel.

Wet Lay-up: A method of making a reinforced product by applying a liquid resin system while the reinforcement is put in place.

Wet Strength: The strength of an organic matrix composite when the matrix resin is saturated with absorbed moisture. (See Saturation).

Whisker: A short single crystal fiber or filament. Whisker diameters range from 1 to 25 microns, with aspect ratios between 100 and 15,000.

Work Life: The period during which a compound, after mixing with a catalyst, solvent, or other compounding ingredient, remains suitable for its intended use.

Woven Fabric Composite: A major form of advanced composites in which the fiber constituent consists of woven fabric. A woven fabric composite normally is a laminate comprised of a number of laminae, each of which consists of one layer of fabric embedded in the selected matrix material. Individual fabric laminae are directionally oriented and combined into specific multiaxial laminates for application to specific envelopes of strength and stiffness requirements.

Yarn: A generic term for strands or bundles of continuous filaments or fibers, usually twisted and suitable for making textile fabric.

Yield Strength: The stress at which a material exhibits a specified limiting deviation from the proportionality of stress to strain. (The deviation is expressed in terms of strain such as 0.2 percent for the Offset Method or 0.5 percent for the Total Extension Under Load Method.)

X-Axis: In composite laminates, an axis in the plane of the laminate which is used as the 0 degree reference for designating the angle of a lamina.

X-Y Plane: In composite laminates, the reference plane parallel to the plane of the laminate.

Y-Axis: In composite laminates, the axis in the plane of the laminate which is perpendicular to the x- axis.

Z-Axis: In composite laminates, the reference axis normal to the plane of the laminate.

SOME COMMON TERMS FOR NATURAL FIBERS, YARN & FABRIC (not limitative)

Areal Density: It is the weight of fabric per unit area.

Bale: A package of raw natural fibers, usually weighing up to 150 kg.

Braiding: The process of interlacing three or more threads is made in such a way that they cross each other and are laid together in a diagonal formation. Flat, tubular, or solid constructions may be formed together in this way.

Canvas: A plain weave cloth generally double warp and single weft inter-woven, weighting not less than 400 g/m2.

Carding: Process step that cleans and separates the fibers, mixes them and forms to a sliver.

Decortication: A process of separating the fibrous matter from pithy or woody matter.

Draft: The amount of attenuation of textile material at different stages of spinning preparatory and spinning process.

Fill (Filling) or Weft: In a woven fabric, the yarn running from selvage to selvage at right angles to the warp.

Hackling: A combing process by which the long and short fibers, including the non fibrous materials are separated. Generally done before carding. Also results in oriented fibers.

Hessian (or Burlap): A single warp plain weave (jute) fabric weighing from 140 to 450 grams per metre with a normal basic width of 100 cm being manufactured in various widths and weight / area, up to a maximum of 500 g/m2.

Linear Density: Mass per unit length for any textile fibre, sliver or yarn.

Mildew: A fungal growth on any material.

Nonwoven: A fabric-like textile structure, having wide range of thickness and being produced from an assembly of fibres (with random or parallel orientation) by applying bonding with adhesive / thermal treatment / needle punching.

Plain Weave: The type of weave in a cloth in which each warp thread or a pair of warp threads pass alternatively over and under each weft thread.

Ply Yarn: An assembly of two/more single yarns twisted together in a direction (say, S) opposite to that say, Z) in its component single yarns to have a balanced twisted structure.

Sliver: The long continuous ribbon of fibres, loosely held together, that comes out from the carding and drawing machines.

Tex: The universal unit for yarn count; it is the weight in grams per kilometer of yarn.

Twill Weave: A weave that produces diagonal lines on the surface of the cloth

Twine: A plied yarn formed by twisting together two or more strands of yarns.

Warp: The longitudinally oriented yarn in a woven fabric (see Fill/weft); a group of yarns in long lengths and approximately parallel.

Weave: The type of interlacement of warp and weft to form a fabric.

Yarn: A product of substantial length and relatively small cross-section of fibres and/or filaments with or without twist.

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48 5563 545 649$ 7344 8056 NN43 FF54  7777 059  389  6290  447 yyy 34 36
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THERE IS A DIFFERENCE
BETWEEN KNOWING
THE PATH
AND WALKING THE PATH

Morpheus
The Matrix

References

Ashby M. & Johnson K (2010), Materials and Design, 2nd Edition, Butterworth-Heinemann.

Ashby M (2009), Materials and the Environment, Butterworth-Heinemann.

Ashby M (2004), Materials and Product Design, Engineering Department, Trumpington Street, Cambridge and the Royal College of Art, Kensington Gore, London.

European Bioplastics (2014), Frequently asked question on bioplastics.

Karana E (2009), Meaning of Materials, PhD Thesis, Delft University of Technology.

Shen L, Haufe, Patel M (2009), Product overview & market projection of emerging bio-based plastics, Final report, PRO-BIP 2009. Corpernicus Institute for sustainable development and innovation, University of Utrecht, The Netherlands.

Thierry Renault (2013), Faurecia Automotive Seating.

Sur D (2005), Understanding Jute Yarn, 1st Edition, Anindita Sur.

Van Kesteren I, Selecting materials in product design (2008), PhD Thesis, Delft University of Technology.

US Department of Defence (2002), MIL-HDBK-17-1F, Volume 1, Composite Materials Handbook, Polymer matrix compositesguidelines for characterization.

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Various images, Susan Mossman - Early Plastics: Perspectives 1850 – 1950, Science Museum London 1997
Source:www.jiscdigitalmedia.ac.uk.
www.emil-berliner-studios.com/en/chronik1.html, Accessed 24 Dec 2014.
Medallions Pope Pius IX. Bois Durci, 1870, Dm. 11 cm
Accessed 24 Dec 2014. http://de.wikipedia.org/wiki/Bois_Durci
Magdalena Abakanowicz, www.abakanowicz.art.pl
Metropolitan Museum.
Science Museum, London.
Dunagro, The Netherlands. www.dunagro.nl

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NFCDesign platform

NFCDesign platform consists of a core group of persons working in industry, product design, Universities and knowledge centers and government. The core group consisted of:

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Indulge & Explore
Natural Fiber Composites

An invitation to product designers

Dilip Tambyrajah
March 2015

NFC design