A Bio-based fibre-reinforced plastic pedestrian bridge for Schiphol

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Summary

The present paper investigates Bio-based fibre-reinforced plastics, used as a load-bearing element of a bridge. We aim to increase the renewable content and decreasing the embodied energy of FRP. To achieve that, the consisting raw materials of these plastics which are based on non-renewable resources, are substituted by alternative less energy intensive materials produced from biological renewable resources. The research focuses on the potentials of natural fibres for a successful substitution of artificial fibres used as reinforcement in load-bearing polymer composites, while bio-based resins and natural core materials are analysed as well. The result of the research is applied on a real case scenario of a lightweight structure, a pedestrian bridge in Schiphol Logistics Park, a logistics zone under development adjacent to Amsterdam's International Airport.

Keywords: bio-based FRP bridge; natural fibres; bio-plastics; bio-resins; load-bearing FRP; flax; jute; basalt; glass fibre;

1. Introduction

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

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

The automotive industry is a sector that has replaced extensively most conventional fibre-reinforced plastics with bio-based composites while industrial designers have successfully created bio-based plastic products such as furniture. On the contrary, in the building industry the use of bio-based composites is vastly limited in applications that mainly consist of facade cladding components, flooring and connections. Even more, in the case of structural applications, the use of bio-based polymers and natural fibres is not yet tested on real projects and has only been investigated at a research level.

2. Fibres

This chapter aims to determine whether bio fibres are suitable for application in our bio bridge and to determine whether other non-organic fibres can be good sustainable alternatives to the conventional fibres like Glass or Carbon.

Fibres are generally classified into mineral fibres (made from glass), polymer fibres (synthetic), metal fibres and natural fibres[1]. Inorganic fibres, excluding only carbon fibres, are made from solid raw materials by production methods based on melting and stretching processes. One the contrary, natural fibres such as wool or plant fibres already occur in the form of fibre and so they are collected and refined in order to become an industrial product.

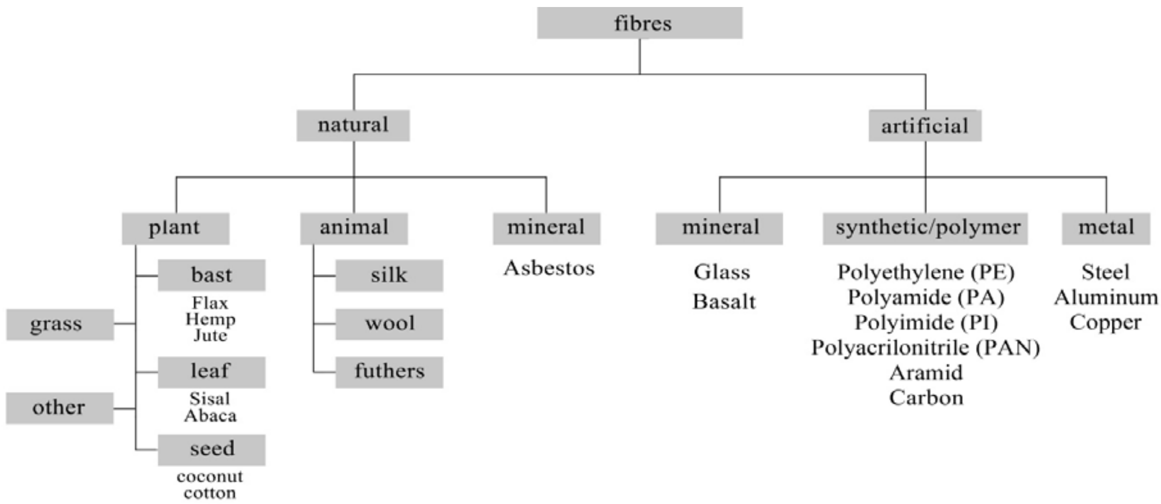


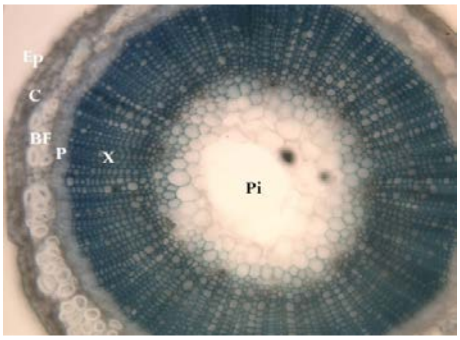
Fig. 1: Classification of fibres

2.1 Natural fibres

As previously mentioned, the term natural fibres refers to fibres that occur in nature, and are found in plants (cellulose fibres), animals (protein fibres) and minerals (asbestos). However, when it comes to fibre-reinforcement for polymer composites plant fibres are preferred due to their superior mechanical performance compared to animal and mineral fibres. Cellulosic fibres are obtained from various parts of plants, such as the seeds (cotton, kapok), stems (flax, jute, hemp, ramie, kenaf, nettle, bamboo), leaves (sisal, manila, abaca), fruits (coconut, coir) and other grass fibres. Similar to artificial fibres, natural plant fibres can be processed to produce different types of technical textiles commonly in the form of woven fabrics, non-crimp fabrics, chopped strand mats and fleeces.

Apart from their renewable resource, plant fibres are also non-toxic which in combination with their exceptional thermal and acoustic insulating properties makes them suitable for use as insulating products in the form of panels, batts or ceiling boards. Due to their abundance, natural fibres are considered as a low cost alternative, mainly as a primary product. Specific fibre species, though, usually in the form of textile, exceed in price fabrics based on artificial fibres.

Typically, plant fibres contain 60-80% cellulose, 5-20% lignin and moisture up to 20%[2]. Cellulose, hemicellulose, and lignin are organic polymer compounds that consist the major constituents with percentages that vary depending on the species and the variety of the plant, agricultural variables such as soil quality, the weathering conditions, the level of plant maturity and the quality of the refining process.



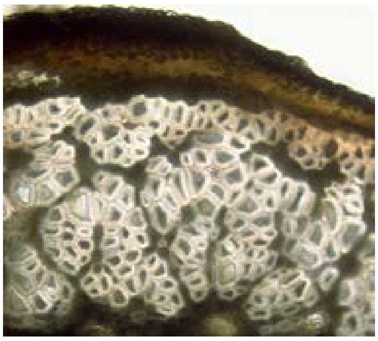
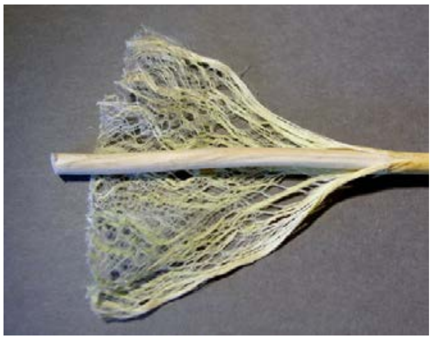



Fig. 2, 3: Cross-section of flax (left) and hemp (right) stem under the microscope
Fig. 4: Extraction of dry hemp fibres from the outer skin (decortication)

2.1.2 Mechanical properties

In general, the fibres of the long stems of plants, also known as bast fibres, exhibit better mechanical properties compared to other plant categories and therefore they are preferred for the building industry. In this plant category, the fibres are concentrated in the outer skin of the stalks (Fig. 4) supporting the conductive cells and providing strength to the stem. Having a length of a few centimetres, these fibres are characterized by high tensile strength, though lower than artificial fibres.

Table 1: Mechanical properties of selected natural and artificial fibres

Fibres	Young Modulus (GPa)	Strength (MPa)	Density (g/cm^3)	Specific Modulus	Specific Strength
Basalt	90	1430-4900	2,67	33	~1185
E-glass	72	2000-3500	2,54	28	~1080
Flax	50-70	500-900	1,4-1,5	~42	~480
Hemp	30-60	300-800	1,48	~30	~370
Jute	20-55	200-500	1,3-1,5	~27	~250

One of the greatest advantages of plant fibres is their low density. This results in components that can be much more lightweight than common glass fibre-reinforced composites. Consequently, having a low weight, specific strength and specific stiffness, which is the materials strength and stiffness divided by its density, are increased. Table 1 compares original and specific mechanical properties of three natural plant fibres with exceptional characteristics with two artificial counterparts, E-glass and basalt fibre. It is clear that natural fibres have a significant performance in stiffness which is advantageous especially in structures designed for bending stiffness, such as bridges.

The mechanical properties of plant fibres are strongly influenced by the growing environment. Conditions such as temperature, humidity, soil composition and air quality affect the height of the plant, the strength and the density of its fibres. Additionally, the way the plants are harvested and processed results in variations within the properties as well. It is therefore very difficult to achieve precise quality characterization of these fibres. After repeated testings the results often deviate.

Another important reason for the large spread in the mechanical properties of natural fibres is the defects on the structure of the fibre, produced irreversibly either during plant growth or decortication process[3]. During a tensile test, the break usually occurs where the defect is situated.

2.1.3 Durability

One of the biggest drawbacks of cellulosic fibres is their hydrophilic behaviour which results in excessive moisture absorption from their environment. Several studies[4,5] conclude that this is the main reason that causes accelerated reduction of their mechanical performance. Water inside the fibre molecules behaves as a plasticizer, allowing cellulose molecules to move freely. This is continuously repeated process of absorbing and evaporating moisture, depending on different seasons, which causes the elastic modulus and tensile strength to decrease. The decrease in mechanical properties might be also because of fungus development due to internal moisture of fibre.

Poor compatibility between hydrophilic cellulosic fibres and hydrophobic resins is another reason responsible for the degradation and loss of strength caused by premature ageing[6]. Due to this poor adhesion between the two materials, load transfer from matrix to fibres is not good, which may lead to a low quality product that can meet bonding failure with age.

Natural lignocellulosic fibres, being composed of carbon, hydrogen and oxygen are characterized for their high sensitivity to heat, as carbon is a main highly flammable element. Thus subjection of plant fibres to a constant temperature of 180oC can cause decrease of the mechanical properties while temperatures above 200oC destroy completely the fibres. Plant fibres are also susceptible to UV radiation. Photochemical degradation by UV light results in changes in the molecular structure of the composite that promote surface embrittlement, cracking, discolouring and loss of tensile and impact strength.

2.1.4 Chemical treatment of plant fibres

In order to improve durability of natural fibres, many researchers have been focusing on developing different treatment methods. These treatments are either physical or chemical methods that lead to reduction in moisture gain and improvement of the fibre-matrix adhesion by modifying the fibre surface, morphology and composition[7]. However, these methods are still at an early stage of development regarding cellulosic fibres and yet they are not introduced in the fibre production process.

2.2 Artificial fibres

Because of the poor durability issues that we encountered when studying bio fibres, a few common and less common artificial fibres have been studied by us.

Contrary to natural, man-made fibres do not originally exist in the form of a fibre. Fibre-forming materials are usually extruded and drawn through little holes, in order to be formed into thin threads. The fibre-forming materials can be synthetic, metallic or other inorganic. Synthetic fibres are composed of polymers obtained from petrochemical resources, such as polyethylene and polyamide while metallic fibres can be out of aluminum or steel and are not used in as reinforcement. A well-known representative of polymer fibre is carbon fibre, which is used exclusively in application with high strength capacity and light weight requirements (automotive, sport, aerospace etc.). Another alternative inorganic fibre-forming material which is mostly used in structural composites is common glass. Finally we mention the rather new mineral based fibre Basalt.

2.2.1 Glass fibre

Glass fibre is produced from molten glass of specific composition of sand, limestone, kaolin, fluorspar and other particles. Different percentages of the consisting materials result in different types of glass that can be produced. E-glass, C-glass and S-, R-, T-glass are well-known fibre types

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

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

Production of glass fibre includes mixing of the consisting materials, import into the melting furnace and finally extrusion of molten glass into thin filaments.

2.2.2 Basalt fibre

Basalt is a variety of hard and dense igneous volcanic rock that originally was created in a molten state. During the last decade, basalt emerged as an alternative of fibre reinforcement in composites. Basalt fibre exhibits superior strength and stiffness even higher than E-glass, while it is highly resistance to fire, moisture, UV radiation, alkaline and acids.

Apart from the mechanical superiority, basalt fibre competes with glass in more ways. Simple composition of basalt fibre, in which no secondary materials are required is one of its advantages. The single feed line carries only crushed basalt which contributes in shortening the entire process and thus energy cost as preparation of various ingredients by weighting and mixing is not needed[8]. Additionally, basalt fibre is non-toxic and easily recycled.

Similar to glass, extraction of the raw material is achieved by typical mining operations. Crushed basalt is then loaded in melting furnaces, from which thin filaments are extruded and processed to yarn and textile fabrication.

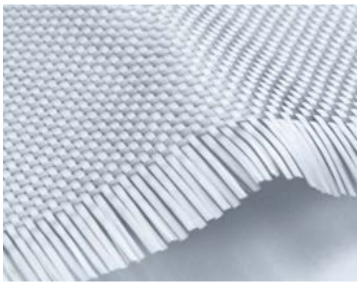


Fig. 5: Glass fibre woven reinforcement *Fig. 6: Basalt fibre unidirectional fabric*
Fig. 7: Grinding process of basalt stone crusher

3. Bio-resins

Aiming to further improve the environmental impact of bio-composites by increasing the percentage of the consisting renewable raw materials, bio-resins have been developed. Bio-resins, known also as bio-based polymers or organic plastics, are synthetic polymers, produced from renewable raw material such as starch, cellulose or agricultural waste products. Depending on their chemical composition, they are classified in biodegradable and durable.

Similar to natural fibres, biodegradable plastics tend to uptake moisture from their environment whereas they are more brittle than petroleum-based resins and exhibit lower heat resistance. Thus, biodegradable plastics are preferred in temporary applications, including packaging and short-lived consumer products. The most common biodegradable polymers are Thermoplastic starch (TPS), Cellulose (tri)acetate (CA, CTA), Polylactide (PLA) and Polyhydroxybutyrate (PHB).

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

This next generation of non-biodegradable resins are the so called durable bio-resins. These plastics, being based on vegetable oil they maximize the content of renewable raw materials while they achieve a long-lasting functionality by the addition of fillers and nano-additives during production. Having long-lasting properties, durable resins are used in applications with longer service life requirements. Durable bio-based plastics that are used as resins in composites include modified polylactic acid (PLA), polyhydroxy alkanoates (PHBV), industrial starch and resins based on castor oils which are produced from agricultural waste, such as furan.

4. Bio-based bridge

In this project the research on natural plant fibres and bio-based resins had the opportunity to be applied on the real project of a lightweight bio-based pedestrian bridge in Schiphol Logistics Park, a logistics area close to the airport of Amsterdam in the Netherlands. The site is divided by a 7-metre wide ditch (measured from the top of the slopes) into two sub-areas, the logistic park and a public green park. The two areas will be connected at one point with the bio-based bridge of this project.

4.1 Design guidelines

The fact that the bridge is a single product and not part of a large production, directs construction towards simple manufacturing techniques suitable for small batch sizes. Regarding the cost of such structures, the mold that is needed is usually the most critical factor. Obviously, in the case of multiple reuses, the mold cost is spread over the butch size of the production and thus it is divided and added on the individual price of each unit. However, as this is not the case for the bridge of this present project, mold-making had to be reconsidered.

Alternative mold solutions towards a cost efficient structure could include the use of materials that can be easily found within most composite construction companies. Flat and bended molding tables or molds that were previously used in other productions and can be easily adjusted and reused, as well as molds by inexpensive new material are ideal elements for constructing a cost-effective mold.

Apart from cost efficiency, another parameter that is also considered to be important for this project is the optimum structural design of the bridge. Having a geometry with an exceptional structural performance contributes not only to a safer bridge but also to the minimization of the material used and thus to a lower embodied energy for the structure.

The last factor regarding the design is related with the aesthetical result and especially with the way plastic material should influence the shape of a bridge. If a truss structure is connected with steel and wood then what the shaping potentials of plastic could be? Plasticity already including the word plastic is used in plastic arts for describing the quality of being plastic and able to be molded. Therefore this is a characteristic that should be reflected on a bridge that was not a result of welding but molding.

4.2 Design

The final design is based on a U-shaped uniform composite structure with a slightly bended deck. The intention of choosing such a shape is to achieve a complete and coherent structural system by using structurally the parapets as beam elements. Separating the structure in one deck element and two side parapets assembled together would prevent continuity of the fibre reinforcement within the composite and thus subdivision of the system. Additionally, in case of a separate structure, the connection points would require special shaping and increase complexity of the mold. One the contrary, a uniform shape avoids the visible connection lines between the deck and the parapets.

Fig. 8: Impressions of the bridge geometry

An important characteristic of the location is a height difference of 0,75m between the two sides of the canal that resulted in an asymmetric and slightly rotated arrangement of the bended deck, as it becomes clear from the longitudinal section (Fig. 9). The parapets of the bridge are placed with an inclination of 30° on the deck (fig. 10), with the low edges making a smooth curved turn, while the height of the parapets varies between a maximum of 1,3m and a minimum of 1,0m.

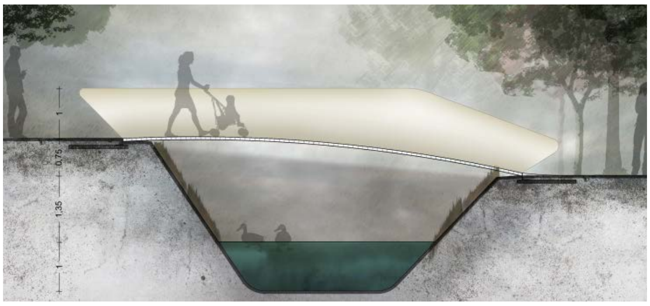


Fig. 9: Longitudinal section

Fig. 10: Transverse section

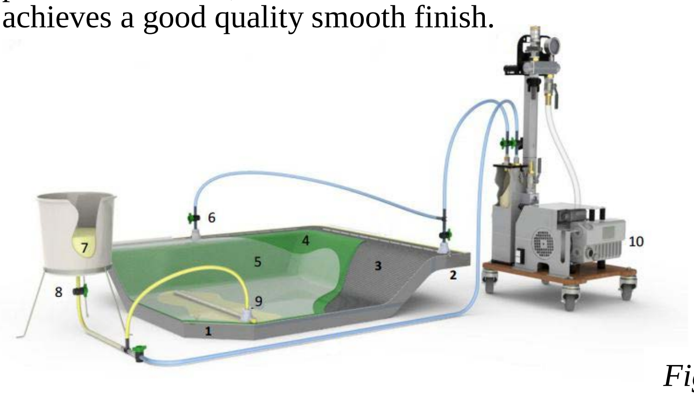
On top view, the span of the bridge develops with an elliptical way. Following this specific shape, the structure introduces a feeling of a surrounding space to a passenger that stands in the middle of the bridge, while the two sides act as entrances to the elliptical deck space. The minimum width of the bridge at the two entrances is 2,0m and it reaches a maximum of 3,0m in the middle. The span has an overall length of 8,2m. After performing the structural calculation, which consists of the following chapter, the thickness of the structure is considered to 7,0mm.

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

4.3 Production method

The manufacturing method that was chosen is the vacuum assisted resin transfer molding (VARTM) or vacuum injection. The process requires a single mold that is used to create the laminate by laying the fabrics of the dry reinforcement and the additional layers on it. Then the laminate is sealed airtight on the mold by a flexible bag that allows injection of the resin through thin tubes and extraction of air by a vacuum pump at the same time. The resin is released and sucked into the bag by the vacuum, flowing through and impregnating the fabric. After completion of the injection, the structure is left to cure before it is removed from the mold.

One of the major advantages of VARTM is that it is an economic process with good quality, appropriate for small butch sizes. Mold costs are lower than other molding processes, as low-cost, disposable materials are normally used for constructing the single molds used in the particular process. However, due to the absence of a second mold only the surface attached to the mold achieves a good quality smooth finish.



1. Mold
2. Sealing flange
3. Dry reinforcement
4. Disposable materials
5. Vacuum bag
6. Vacuum control valve
7. Resin
8. Resin control valve
9. Resin entry points
10. Vacuum pump

Fig. 11: Vacuum assisted resin transfer molding

4. Conclusions

Although the substitution of the conventional consisting materials of fibre-reinforced plastics by renewable plant fibres and bio-based resins is a practise that was primarily investigated decades ago, it is only during the last decade that it has increasingly drawn the interest of different industries. However, the drawbacks of these materials which are based on biological resources prohibit their use in specific sectors, such as the construction. Despite the exceptional mechanical properties of specific natural fibres (flax, jute, hemp) that compete even glass fibre, low durability is their main disadvantage. Excessive moisture uptake, pour compatibility with common resins and low resistance to fire and UV result in premature decrease of their mechanical properties.

Fibre treatment methods proved to be a promising solution to improve durability issues, yet they are still under development. Additionally, chemical treatments increase the non-renewable content and the embodied energy of the product, whereas they have certain toxicity and cost. Thus, alternative biological methods, such as sea water treatment are being researched and developed as cost-effective, sustainable solutions.

Apart from the mechanical-physical properties of natural plant fibres, the type of the textile is also an important factor regarding sustainability of the product. Simple fabric types (chopped strand mats, fleeces, etc) that do not require extensive elaboration of the raw material retain their low embodied energy. However, complex technical textiles used in structural application, such as non-crimp fabrics involve extra processes (spinning, weaving etc) that consequently increase the energy intensity and the environmental impact of the fibre production process.

Considering the environmental impact of cellullosic fibres, agricultural processes from soil preparation until harvest of the plants should also been researched in detail as part of a life-cycle analysis of a textile. For instance, the effect of a chemical fertilizers and pesticides on water and soil quality is only one negative aspect of modern agriculture.

Our research shows that a renewable origin of raw materials does not necessarily classify them as sustainable. Each step of the fibre production process should be analysed in depth and compared with conventional non-renewable based materials. Further research is also required in the field of treatment methods that would eliminate biodegradability of biological products. Until these methods are introduced in the industry and applied on textile products, natural non-durable plant fibres and biodegradable resins are prohibited in load-bearing and durability-demanding structural applications.

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