Natural Fiber Reinforced Composites & Façade Applications

A research on the mechanical performance of plant fiber reinforced bio-resins & its possible façade applications

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I – Introduction

01. Problem Statement

As a result of the growing awareness of the global environmental factors, principals of sustainability, and industrial ecology, the green chemistry and engineering are put to use into the development of the next generation of materials of construction. Unfortunately, the tremendous growth of the petrochemical industry in the 20^{th} century slowed the progress of bio-based products in general, and especially in the building industry. However, the production of materials from the bio-based feedstock are expected to increase up to 25% in the 2030, (Mohanty, et al., 2005). The need of materials independent from petroleum resources is considered a priority on the European's Union's development strategies and environmental challenges.

Composite materials are considered attractive due to their ability to combine material properties in ways not found in nature. The combination of these material properties often results in lightweight structures having high stiffness and personalized properties for specific applications. Therefore, saving weight, and reducing energy needs. Fiber-reinforced polymer composites began in 1908 with cellulose fibers. Today, glass fiber is the leading fiber and is used up to 95% of cases to reinforce a composite. However, researches showed that in some composite's applications, natural fibers demonstrate competitive performances, these composites are known as bio-composites. Bio-composites are defined as a combination of fibers from natural origins and non-petroleum derived or biodegradable polymers.

02. Research objective

The focus of this research is the exploration of plant-based fiber reinforced bio-polymers and their potential use on the building envelope. Through this research the material explored will be referred to as "non-wood natural fiber reinforced composites". Non-wood natural fiber reinforced composites represent a non-traditional sustainable material that could be considered as a sustainable material in the building sector. As a result of its comparable mechanical properties with other non-conventional fiber reinforced composites, it became crucial to explore this material as a construction material for the building envelope.

The objective of this research is to understand the mechanical performance of this material when subjected to humidity, temperature, and UV radiation, in the aim to explore its possible façade applications. Therefore, at the end of this research it is expected to deliver (1) an overview of the natural fibers, and bio-polymers, including their mechanical properties. (2) A comparison between the mechanical properties of non-wood natural fibers reinforced bio-composites and petroleum/fossil-based fiber reinforced composites, before and after subjection to accelerated weathering conditions. (3) Explore the common manufacturing techniques of bio-based composites and their design limitations. (4) Finally, part of the research will be dedicated to the application this material on the building envelope. It is expected during the final part of the research to deliver a complete, and detailed design of a specific façade application using non-wood natural fiber reinforced composite.

03. Research question

The research question to be answered through this research is: *How does non-wood natural fiber reinforced composites perform when subjected to water, temperature, and UV radiations, and how can it be applied on the building envelope?*

04. Sub-questions

1- What are the best suitable non-wood natural fibers and bio-based resins in terms of mechanical properties and availability according to the literature?

2- How does non-wood natural fiber reinforced composites compare to petroleum/fossil-based fiber reinforced composites such as glass fiber reinforced composites and carbon fiber reinforced composites?

3- What is the corresponding manufacturing process to the chosen fibers and resins?

4- How can a non-wood natural fiber reinforced composite be applied on the building envelope?

5. Research Methodology

The methodology to conduct the research is divided into 2 parts: (1) Research by experimentation and (2) Research by design. The 2 parts are interrelated and will be conducted simultaneously after finishing the literature review part. The literature review part is the initial part of the research in which background information will be gathered to be used as a base for the experiments that will be held in TU Delft. These background findings will include all needed information regarding fibers, polymers, manufacturing techniques, and composites engineering and design. It is only valid to start the experiment when this information is available and complete.

05.1. Research by Experimentation

With the start of part (1), several mechanical properties of non-wood fiber reinforced composites will be tested:

- Tension (Universal Testing Machine)
- Bending (Three Point Flex Test)
- Water absorption (Drying & Weighing)

These tests will be conducted before and after subjection of the samples to accelerated weathering conditions. This process is used to simulate the outdoor weathering conditions, and assess the reaction of these materials to specific weathering conditions. The accelerated weathering conditions will be done using a UV testing machine, temperature testing machine, and water subjection. Each aspect (UV, temperature, and water), will be tested independently. The reason is to understand independently the effect of each of the aspect on the samples. The samples will be produced at TU Delft following the findings of the literature. Samples will be a combination of non-wood natural fiber reinforced composites and will be compared to glass fiber and carbon fiber reinforced composites. The decision on the fiber's choice was achieved through the literature review and will be explained in later stages, in which information on 22 Natural Fibers was conducted including their composition and mechanical properties, and then properties were compared in a table with glass fiber and carbon fiber. The decision on the polymer choice was achieved through the literature covered 13 polymers (11 Thermosets and 2 Thermoplastics). Decision was made on a comparison done on the polymer's mechanical properties, color, transparency, time of reaction, suitable production technique (since some production techniques are not accessible without access to composite factories). Finally, the production technique was limited to the available equipment's and the ones that could be done manually without the need of big machinery or access to factories.

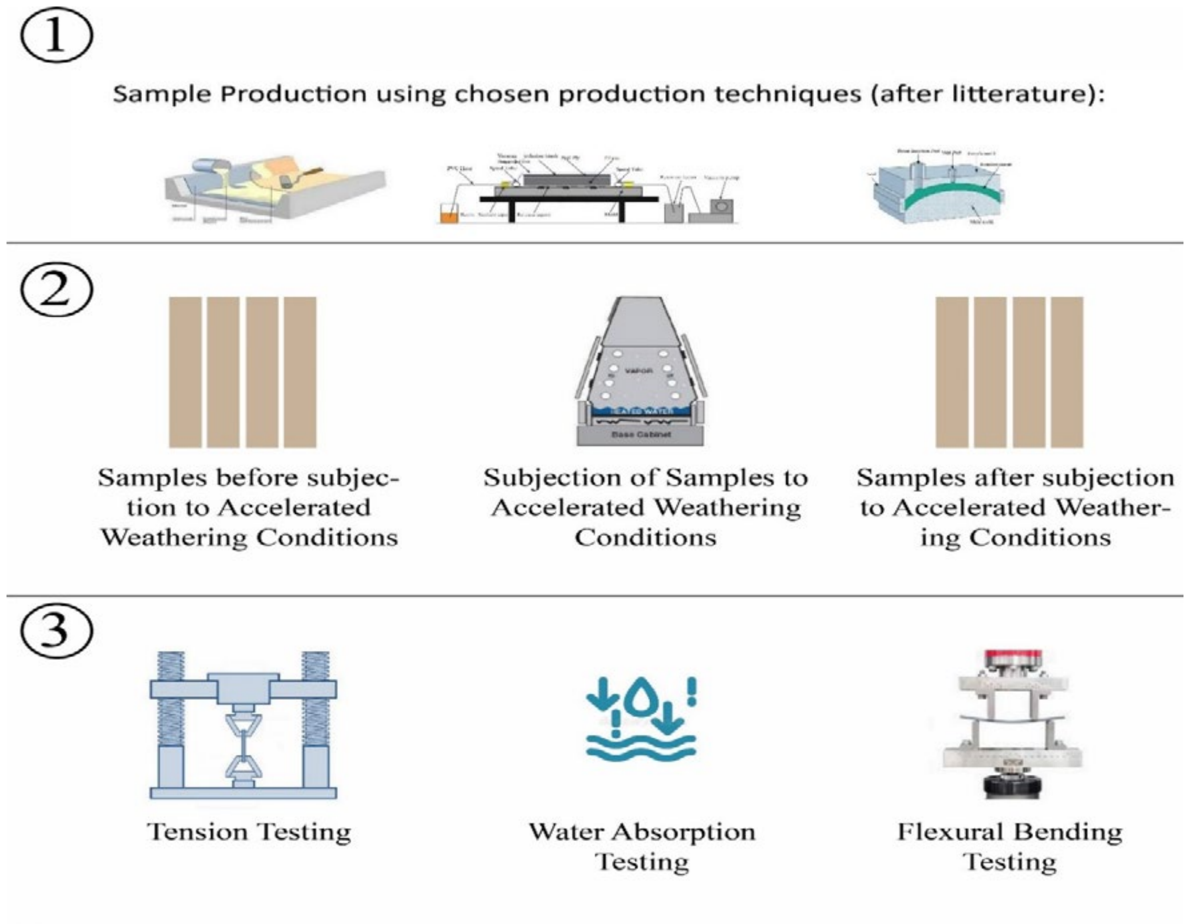


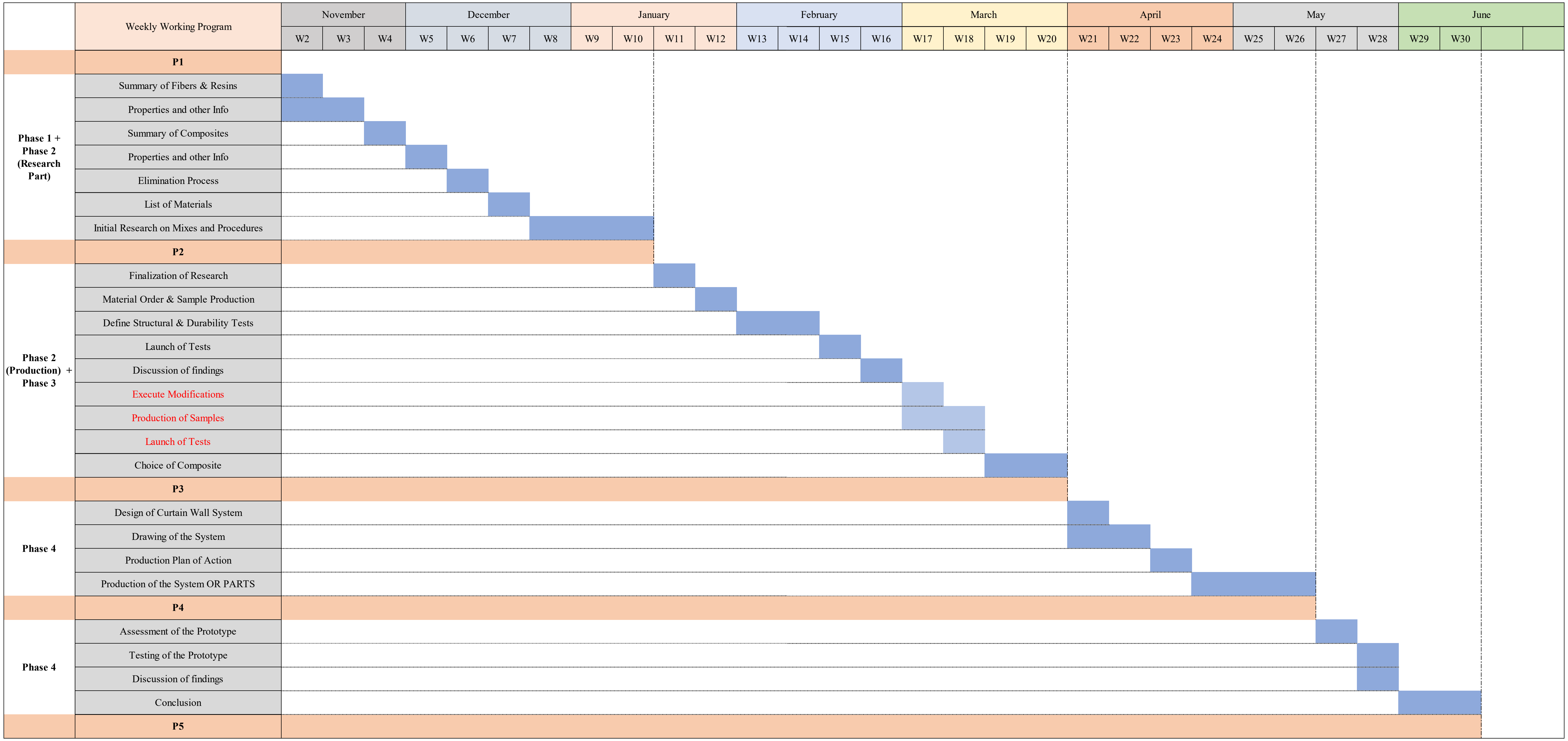
Figure 1. Methodology Scheme

05.2. Research by Design

The second part of the experimentation phase is designated to experiment with the molding of the composites and see to what extent can these composites be deformed and customized to specific building envelope designs.

(2) is the research by design part. This part is basically the part in which a façade component will be designed in detail. Following the findings of the literature and the progress of the experimentation, a façade component will be designed accordingly. Research by design will start first by a brainstorming phase, in which several options of façade applications will be explored. It is crucial to define the objective of the application (protection from environmental factors, decorative, visibility regulation, …) Defining the objective of the application will help in setting the boundaries of the design, since a big number of options could be considered which can make it difficult to decide. After defining the objective, it is important to take into consideration the experimentation progress to start detailing the system accordingly. With that being done, the work on the final objective becomes valid. A clear complete façade system using natural fiber reinforced composites could be designed and detailed. At that stage, several possibilities will be explored in terms of detailing, and several modifications will occur before agreeing on a final outcome. After agreement on a specific application and detail, a prototype will be fabricated. With that, the potential of the material will be presented in a physical model, and combined with scientific data that proves or not prove its relevance.

06. Thesis Schedule



II – Background Research

01.Fibers

Since the start of human time, fiber corps accompanied human civilizations. Individuals used to collect raw fibers to fabricate textiles and ropes. Later, society learned to cultivate such corps. According to Mohanty A.K., et al. (2005), plant fiber corps are the earliest identified plants and individuals continued to domesticate these corps over and over.

Natural fibers are divided based on their ancestries (Mohanty, 2005), they could be resulting from plants, animals, or minerals. Plant fibers include bast fibers, leaf or hard fibers, seed, fruit, wood, cereal straw, and other grass fibers.

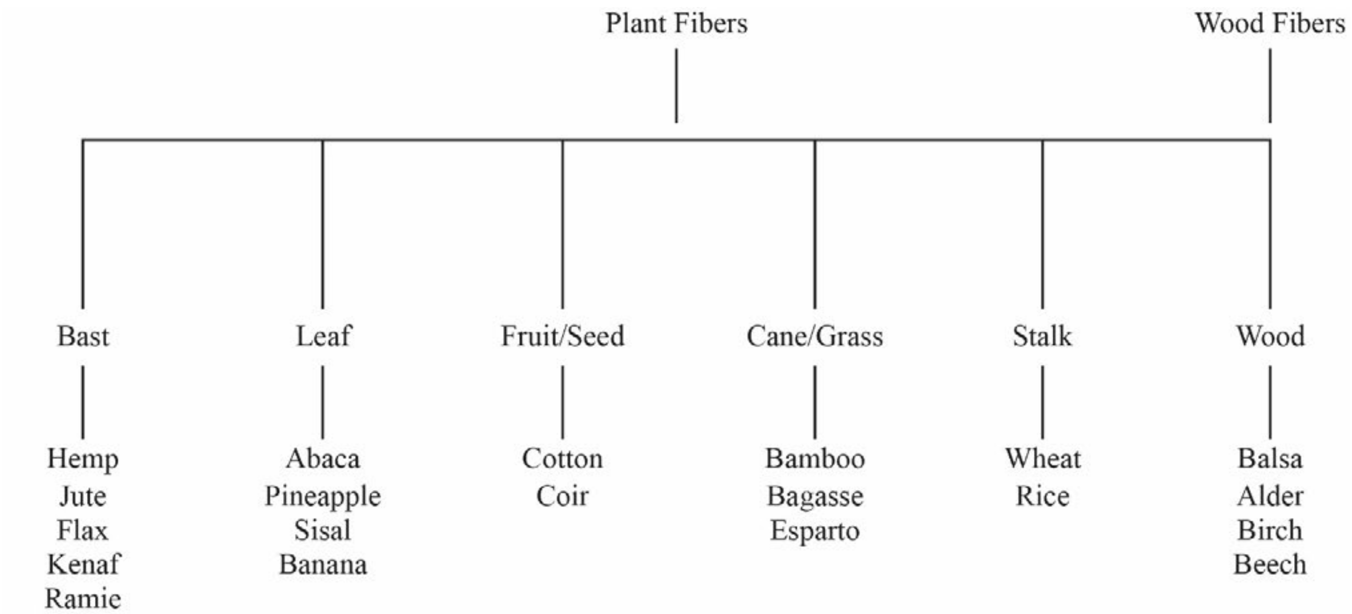


Figure 2. Natural Fibers

01.1. Bast Fibers

Bast fibers have been grown for centuries throughout the world. Bast plants are characterized by long, strong fiber bundles that comprise the outer portion of the stalk. Bast plants include flax, hemp, kenaf, ramie, and jute. These fibrous plants have long been noted for their exceptional strength in cordage and paper, (Lloyd, et al., 1996).

Overall Advantages of Bast Plants (Kozlowski, et al., 1994).**:**

In general, bast plants possess the following benefits:

1) High tensile strength in bast portions, especially in fiber varieties.
2) Bast plants have a relatively low specific gravity of 0.28 - 0.62, yielding an especially high specific strength, i.e., strength to weight ratio.
3) Potential for even greater productivity, bast portions, and mechanical properties through focused genetic breeding.

Overall Limitations of Bast Plants (Kozlowski, et al., 1994)**:**

In general, bast plants also have the following limitations:

1) Relatively high absorption of moisture in core portion.
2) Diminished board properties when using core for particleboard.
3) Difficulty in handling long fiber bundle lengths for processing.
4) Difficulty in applying binder to long fiber bundle lengths.

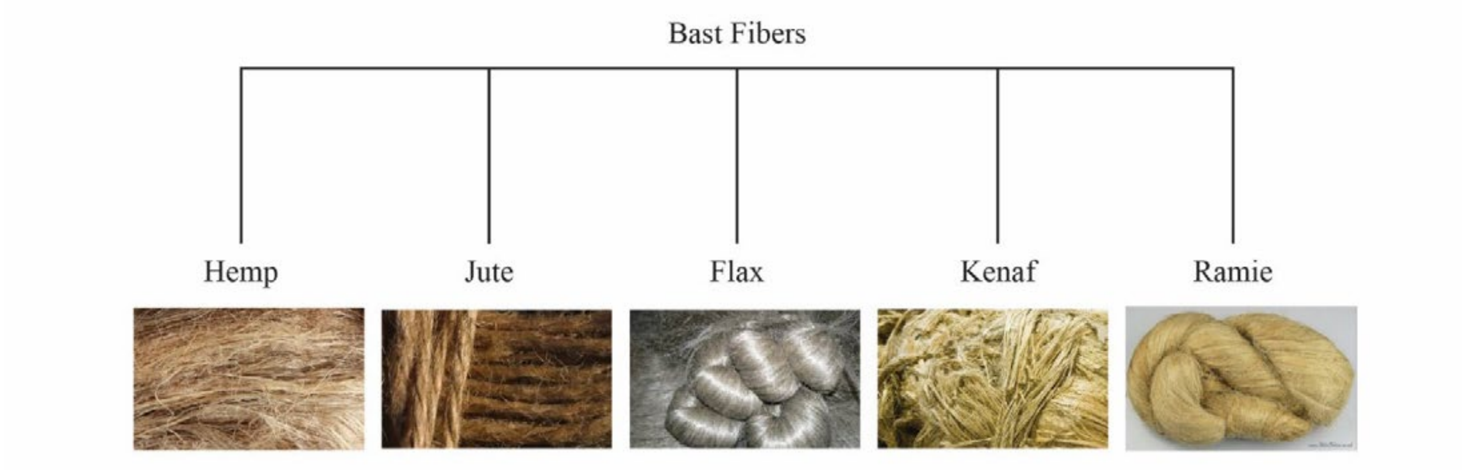


Figure 3. Bast Fibers in Pictures

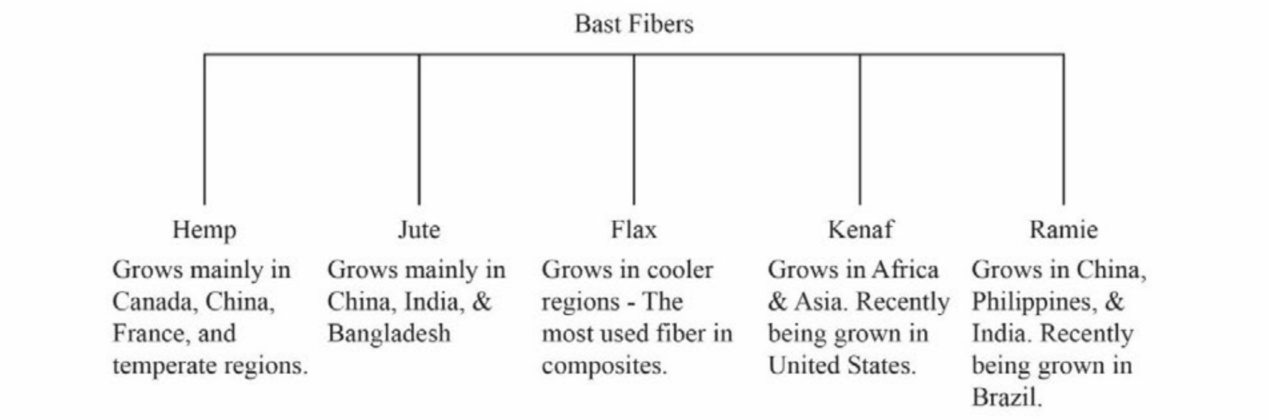


Figure 4. Bast Fibers Growing Regions

01.2. Leaf Fibers

Leaf fiber (also known as hard fiber) is normally obtained by scraping away the nonfibrous material, and the fiber produced can be coarser than other fibers. When obtained from sources such as sisal (agave) and abaca, some of the longest fiber lengths can be obtained (1–4 m). Leaf fiber can have cellulose contents as high as 70%, though they also have low lignin contents compared to wood. Due to their length, the properties of the fibers may change over the course of the fiber. However, pineapple and banana leaves give fibers of much shorter length that are also high in cellulose and low in lignin content.

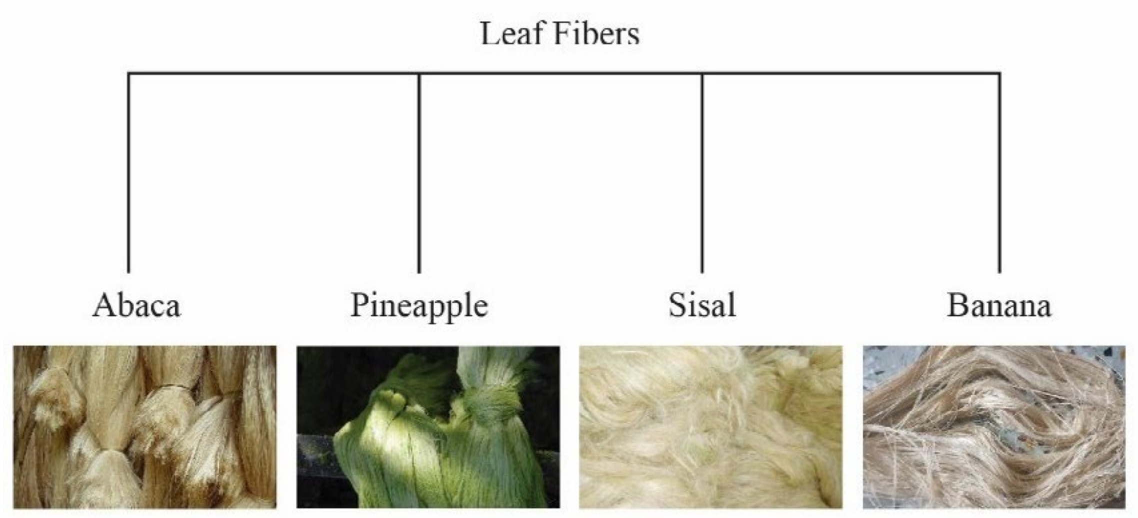


Figure 5. Leaf Fibers in Pictures

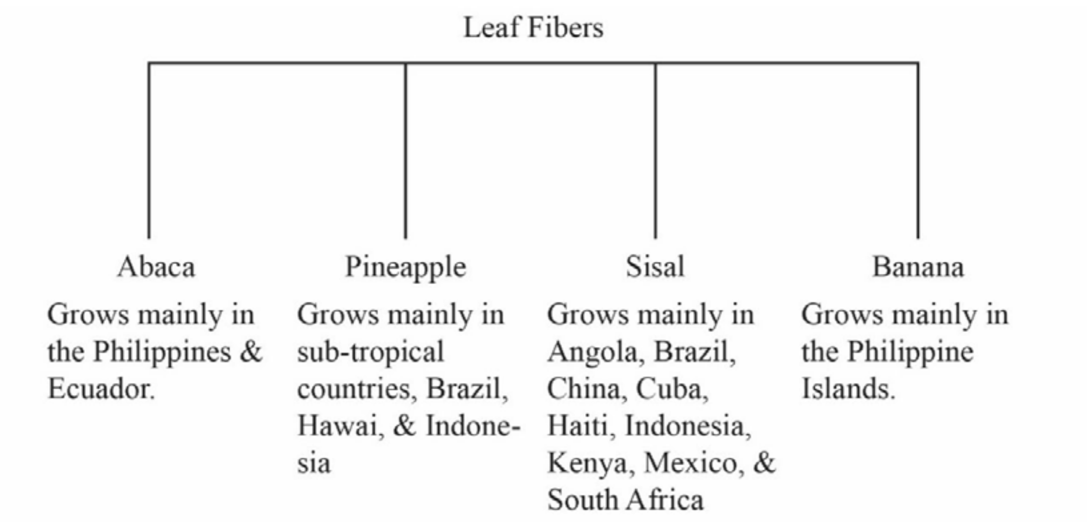


Figure 6. Leaf Fibers Growing Regions

01.3. Fruit/Seed Fibers

One of the most ubiquitous of plants fibers in use is cotton derived from the seed of plants of the cotton (Gossypium) family. Cotton has a three-walled structure consisting of a wax and pectin cuticle, a crystalline cellulose primary wall, a three-layer cellulosic secondary wall and a tertiary wall surrounding the lumen, (Mohanty, 2005).

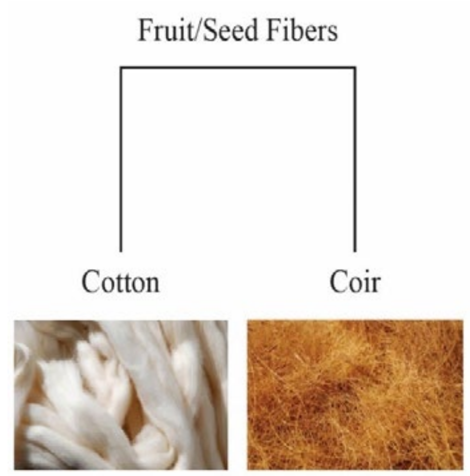


Figure 7. Fruit/Seed Fibers in Pictures

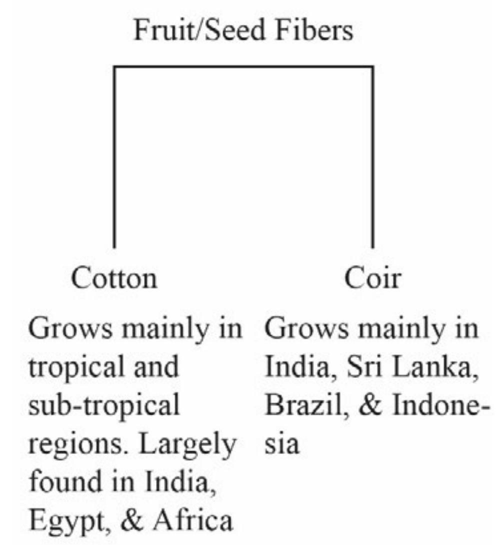


Figure 8. Fruit/Seed Fibers Regions

01.4. Cane/Grass Fibers

Canes such as sugar cane (bagasse) or bamboo, grasses such as Esparto and reeds are also common fiber sources. The canes and reeds have lignin contents higher than bast or straw fibers and, in the case of bamboo, as high as wood fibers, (Mohanty, 2005).

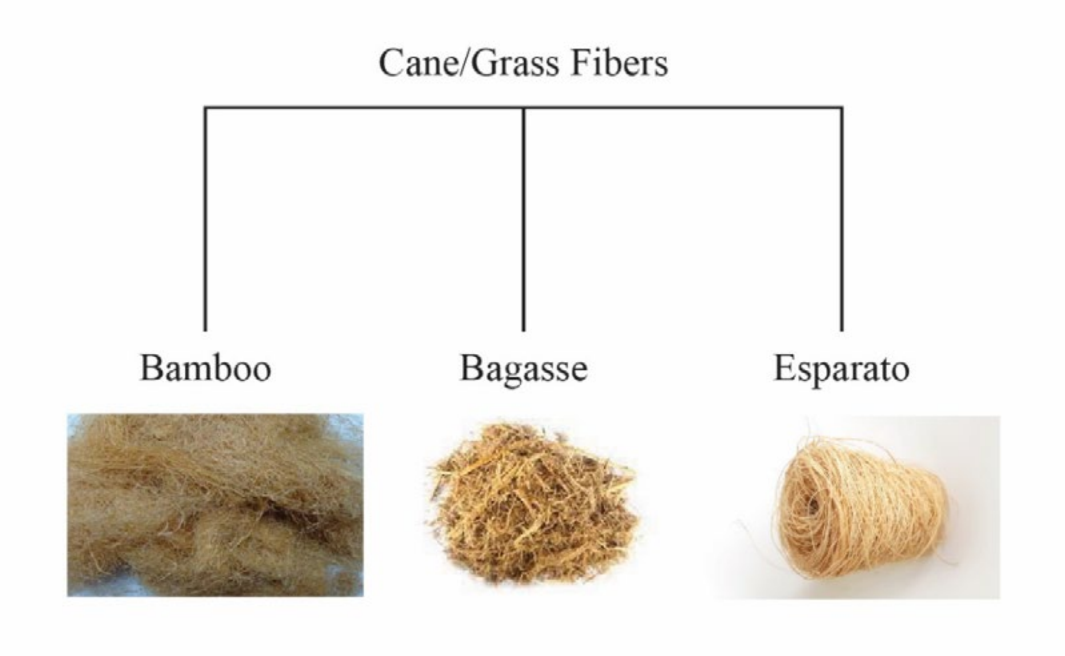


Figure 9. Cane/Grass Fibers in Pictures

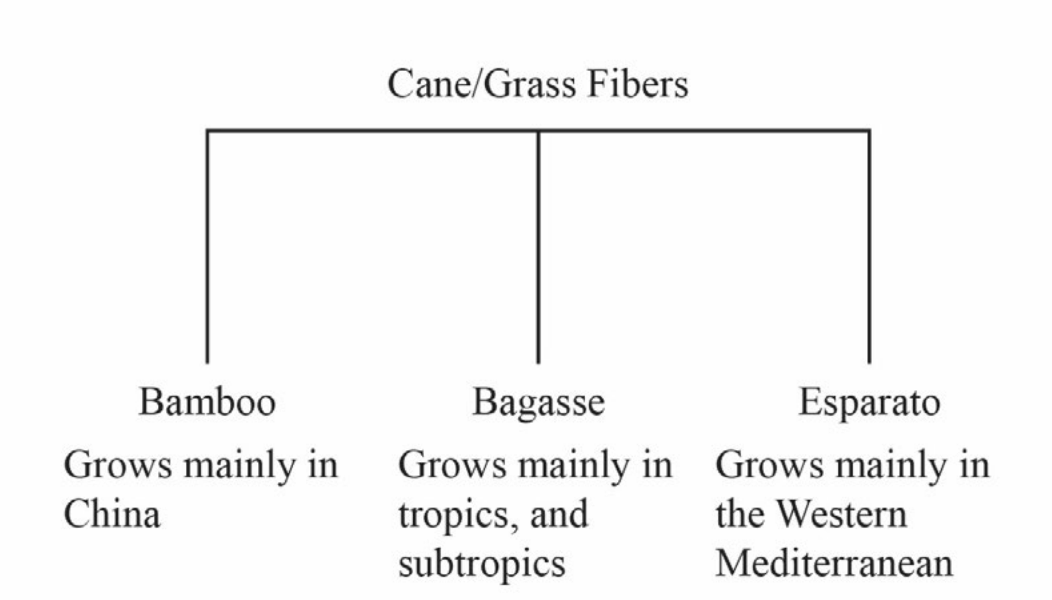


Figure 10. Cane/Grass Fibers Growing Regions

01.5. Inorganic fibers

The term "inorganic fiber" is related to the field of science known as "inorganic chemistry." The field of inorganic chemistry summarizes the chemistry of all inorganic compounds and inorganic materials. For this, it can be stated that inorganic fibers are fibers built up by inorganic materials. In chemistry, usually materials or compounds are distinguished into inorganic and organic ones, (Mahltig, 2018).

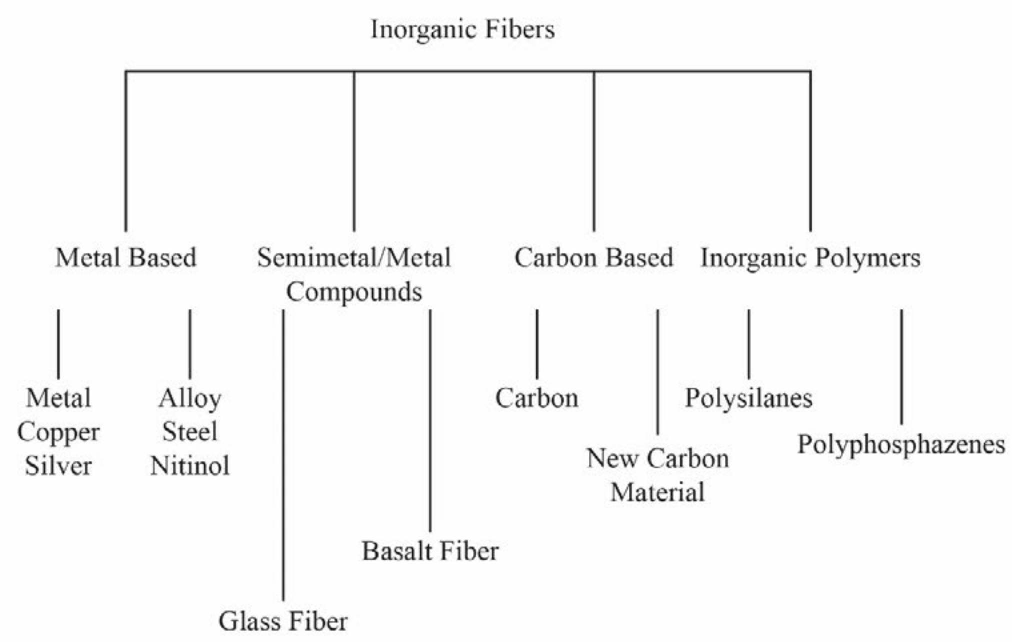


Figure 11. Inorganic Fibers

Glass Fibers:

All glass fibers can be conditionally divided into two main categories: cheap general-purpose fibers and expensive fibers for special applications. Almost 90% of all glass fibers that are produced today in the world are E-grade fiberglass. The mechanical characteristics of glass fibers directly depend on the method of production, the chemical composition of the glass, the temperature, and the environment, (Mahltig, 2018).

E-Glass:

In most cases, E-glass contains 5–6wt% of boron oxide. Modern environmental standards in the United States and Europe prohibit the release of boron into the atmosphere, (Mahltig, 2018).

	Molding Temperature (°C)	Melting Temperature (°C)	Density (g/cm^3)	Strength (MPa)	Elastic Modulus (MPa)	Elongation to Rupture (%)
E-Glass	1160 - 1196	1066 - 1077	2.54 - 2.55	3100 - 3500	76000 - 78000	4.5 - 4.9
S-Glass	1565	1200	2.48 - 2.49	4380 - 4590	8800 - 91000	4.5 - 4.9

Table 1. General Mechanical Properties of E-Glass and S-Glass Fibers

Carbon Fibers:

Carbon fibers can be defined as fibers with a carbon content of 90% or above. The main advantage of carbon fibers compared to other fibers are the high tensile strength, high stiffness, low density, and a high chemical resistance. All these advantages can be combined with an adequate (polymer resin) matrix material to give excellent mechanical properties of composite parts built from both. These composite components are lightweight with very high mechanical properties compared to parts made of metals like aluminum or other fiber-reinforced composites, (Mahltig, 2018).

	Tensile Strength (MPa)	Elastic Modulus (MPa)
Carbon Fiber High Tenacity	3000 - 5000	200000 - 250000

Table 2. General Mechanical Properties of Carbon Fiber

Table 3 present an overview of the chemical and mechanical properties of the commonly used non-wood natural fibers, wood fibers, and inorganic fibers, aiming to create a tool to compare these findings and elaborate a primary selection of non-wood natural fibers that show potential for future experimentation as a composite for building envelop application. Taking the average values of the tensile strength and young modulus of natural plant fibers, it is possible to place them in the following order: Bast fiber > Leaf fiber > seed fiber. According to Lau, A. (2005), Only bast fibers have tensile strength and young modulus comparable to inorganic fibers. It is also clear that bast and leaf fibers have lower elongation at break average compared with other fibers. Fibers with higher elongation at break percentages show lower strength and young

modulus values. According to Ishak et al. (2010), long natural fibers such as bast and leaf fibers have the highest efficiency among the lignocellulosic reinforcements. Research in bio composites, demonstrated the advantages of bast fibers as an excellent material in terms of Stiffness and Strength.

Natural Fibers	Fiber Type	Stiffness (GPa)	Ultimate Stress (MPa)	References
Hemp	Bast	30 -60	300 – 800	Liholt & Lawther (2000)
Flax	Bast	50 -70	500 – 900	Liholt & Lawther (2000)
Jute	Bast	20 -55	200 - 500	Liholt & Lawther (2000)
Sisal	Leaf	9 - 22	100 - 800	Liholt & Lawther (2000)
Softwood	Stem	10 – 50	100 – 170	Anagnost et al. (2002)

Table 4. General Mechanical Properties of Commonly used Plant Fibers in Composites

According to Fan, M. (2015), Flax and hemp bast fibers have been considered the most promising reinforcements for composites; in particular, they were incorporated into the automotive components, as a substitute of glass fiber, and now being considered for their uses in the production of building construction materials.

02. Matrix

The role of the matrix in a fiber-reinforced composite is very crucial to retain the fibers in place, to transfer the stresses between the fibers and to provide a barrier against a hostile environment (chemicals, moisture, …). And finally, to shield the surface of the fibers from mechanical degradation. The matrix has a major influence on the compressive properties of the composite material. It provides a support against the fiber buckling under compressive loading. A polymer is scientifically defined as a long chain molecule containing one or more repeating units of atoms, joint by strong covalent bonds. The collection of large number of these molecules becomes a polymeric material (usually called plastic), (Mallick, 2007).

Polymers are divided into two broad categories:

Thermoplastics: (Drobny, 2007)

The individual molecules of a thermoplastic polymer are not joined together chemically. They are connected by weak secondary bonds that could be temporary broken under the application of heat. The molecules now can be moved to form a new configuration if pressure is applied. On cooling, the molecules can be frozen in their new configuration and the secondary bonds are restored, resulting in a new solid shape. Therefore, a thermoplastic polymer could be heat-softened, melted, and reshaped as many times as desired.

Thermosets: (Al Maadeed, et al., 2020)

In a thermoset polymer, the molecules are joined together by cross-links, forming a rigid network structure. Once they are formed during the polymerization reaction, the thermoset cannot be melted by heat application. The choice of the matrix, basically depends on the mechanical properties of a thermoset or a thermoplastic polymer.

3 major properties are desirable when finding a high-performance composite:

1- High tensile modulus: Influence on compressive strength of composite
2- High tensile strength: Influence on interplay cracking in a composite laminate
3- High fracture toughness: controlling the crack growth in a composite material

Other important considerations such as the stability of the matrix on elevated temperatures and its resistance to moisture or solvents. When referring to elevated temperatures, it means that a polymer must have a high glass transition temperature Tg. Tg must be higher to the maximal use temperature.

	Advantages	Disadvantages
Thermoset Polymer	- Strong thermal stability - Strong chemical resistance - Less creep - Less stress relaxation	- Limited storage life - Long fabrication time in the mold - Low strain to failure - Low impact strength

Table 5. Advantages and Disadvantages of Thermoset Polymers

	Advantages	Disadvantage
Thermoplastic Polymer	- High impact strength - High fracture resistance - High strain to failure - Unlimited storage life - Shorter fabrication time - Post-formability (thermoforming)	- High solution viscosities - Incorporation of continuous fibers is difficult - Low creep resistance - Low thermal stability

Table 6. Advantages and Disadvantages of Thermoplastic Polymer

2.1. Thermoplastics

02.1.1 High Density Polyethylene

It is considered an amorphous material that could behave as a rubbery or glassy material depending on its glass transition temperature. HDPE has both structures; therefore, it gives high toughness at room temperature. However, on low temperature, the toughness tends to decrease that HDPE behaves like brittle, glassy materials, (Subramanian, 2015).

Properties	Value	Reference
Density (g.cm3)	0.961	(Mallick, 2008)
Melting Temperature (C)	145	(Mallick, 2008)
Glass Transition Temperature (C)	-120	(Mallick, 2008)
Crystallinity (%)	77	(Mallick, 2008)
Thermal conductivity (W.m-1. K-1)	0.35	(Mallick, 2008)
Specific heat capacity (C)	1.90	(Mallick, 2008)

Table 7. Common Mechanical Properties of HDPE

02.1.2.Polypropylene (PP)

The mechanical properties of PP vary depending on the degree of crystallinity, molecular weight, and molecular weight distribution. It is found hard to make PP flame retardant because of its excessive thermal degradation, which releases a huge amount of fuel into the flame. PP contributed in automotive industries, home appliances, and other industrial applications. In terms of thermoforming process, it could only be done on a very narrow range of temperature that is close to the melting point of the polymer. Polypropylene is stiffer than Polyethylene. It has high heat distortion temperature. It offers excellent chemical resistance, environmental stress cracking resistance and surface hardness, (Subramanian, 2015).

Properties	Value	Reference
Density (g.cm3)	0.900	(Mallick, 2008)
Melting Temperature (C)	165	(Mallick, 2008)
Glass Transition Temperature (C)	18	(Mallick, 2008)
Crystallinity (%)	123	(Mallick, 2008)
Thermal conductivity (W.m-1. K-1)	0.25	(Mallick, 2008)
Specific heat capacity (C)	1.05	(Mallick, 2008)

Table 8. Common Mechanical Properties of PP

02.1.3.Poly (vinyl chloride):

PVC is commercially a very important polymer. It suffers from poor thermal and light stability, (Mallick, 2008).

Properties	Value	Reference
Density (g.cm3)	1.4	(Mallick, 2008)
Melting Temperature (C)	175	(Mallick, 2008)
Glass Transition Temperature (C)	87	(Mallick, 2008)
Thermal conductivity (W.m-1. K-1)	0.15	(Mallick, 2008)
Specific heat capacity (C)	1.05	(Mallick, 2008)

Table 9. Common Mechanical Properties of PVC

02.1.4.Poly (methyl methacrylate)

PMMA is a transparent amorphous polymer and has been widely used in materials for optical devices. It has many advantages such as good flexibility, high strength, and excellent dimensional stability. PMMA has an excellent transparency in visible spectrum. As a disadvantage, it has poor heat resistance, (Subramanian, 2015).

Properties	Value	Reference
Density (g.cm3)	1.19	(Mallick, 2008)
Melting Temperature (C)	160	(Mallick, 2008)
Glass Transition Temperature (C)	107	(Mallick, 2008)
Thermal conductivity (W.m-1.K-1)	0.19	(Mallick, 2008)
Specific heat capacity (C)	1.39	(Mallick, 2008)

Table 10. Common Mechanical Properties of PMMA

02.1.5. Polystyrene:

It is a conventional product being atactic and amorphous allowing it to be a transparent material. It is characterized by increased brittleness and more difficult processability due to a high melting point. It is resistant to alkalis, acids, oxidizing and reducing agents, (Subramanian, 2015).

Properties	Value	Reference
Density (g.cm3)	1.14	(Mallick, 2008)
Melting Temperature (C)	265	(Mallick, 2008)
Glass Transition Temperature (C)	50	(Mallick, 2008)
Thermal conductivity (W.m-1.K-1)	0.25	(Mallick, 2008)
Specific heat capacity (C)	1.70	(Mallick, 2008)

Table 11. Common Mechanical Properties of Polystyrene

02.1.6.Polycarbonate:

Polycarbonate is a thermoplastic material that offers manufacturers and designers opportunities for design freedom, aesthetics enhancements and cost reductions. PC is known for maintaining coloring and strength over the time, even in stressful conditions. Become an expert with this comprehensive guide and learn all essentials you need to know about this widely used polymer, (Subramanian, 2015). Polycarbonate is a high-performance tough, amorphous and transparent thermoplastic polymer with organic functional groups linked together by carbonate groups and offers a unique combination of properties. PC is popularly used as an engineering plastic owing to its unique features that include: High impact strength - High dimensional stability.

Properties	Value	Reference
Density (g.cm3)	1.15	(Mallick, 2008)
Melting Temperature (C)	160	(Mallick, 2008)
Glass Transition Temperature (C)	180	(Mallick, 2008)
Thermal conductivity (W.m-1.K-1)	0.19	(Mallick, 2008)
Specific heat capacity (C)	1.2 kJ/(kg.K)	(Mallick, 2008)

Table 12. Common Mechanical Properties of PC

02.2. Thermoset

02.2.1. Epoxy Resin

The most frequently used thermosetting resins in composite processing are Epoxies. Resin mix is normally prepared by mixing resin with the catalyst, which starts an exothermic curing reaction. Additionally, other substances may also be added, such as accelerator, fillers, pigments and solvents. The required pressure and heat can then be applied to accelerate the curing reaction, (Fan, et al., 2017).

Properties	Value	Reference
Density (g.cm3)	1.2 – 1.3	(Fan, et al., 2017)
Tensile Strength (MPa)	55 - 130	(Fan, et al., 2017)
Tensile Modulus (GPa)	2.75 – 4.10	(Fan, et al., 2017)
Coef. Thermal Expansion (10^{-6}m/m per ^{o}C)	50 -80	(Fan, et al., 2017)
Poisson's Ratio	0.2 – 0.33	(Fan, et al., 2017)

Table 14. General Mechanical Properties of Epoxy

Epoxy matrix, as a class, has the following advantages over other thermoset matrices:

1. Wide variety of properties, since a large number of starting materials, curing agents, and modifiers are available.
2. Absence of volatile matters during cure.
3. Low shrinkage during cure.
4. Excellent resistance to chemicals and solvents.
5. Excellent adhesion to a wide variety of fillers, fibers, and other substrates.

The principal disadvantages are its relatively high cost and long cure time, (Fan, et al., 2017).

02.2.2. Polyester Resin

Polyester resins can be formulated in a variety of properties ranging from hard and brittle to soft and flexible. Its advantages are low viscosity, fast cure time, and low cost. Its properties are generally lower than those for epoxies. The principal disadvantage of polyesters over epoxies is their high volumetric shrinkage. Although this allows easier release of parts from the mold, the difference in shrinkage between the resin and fibers results in uneven depressions (called sink marks) on the molded surface. The sink marks are undesirable for exterior surfaces requiring high gloss and good appearance. As in the case of epoxy resins, the properties of polyester resins depend strongly on the cross-link density. The modulus, glass transition temperature, and thermal stability of cured polyester resins are improved by increasing the cross-link density, but the strain-to-failure and impact energy are reduced, (Mallick, 2008).

Properties	Value	Reference
Density (g.cm3)	1.1 – 1.43	(Mallick, 2008)
Tensile Strength (MPa)	34.5 – 103.5	(Mallick, 2008)
Tensile Modulus (GPa)	2.1 – 3.45	(Mallick, 2008)
Elongation at Break (%)	1 - 5	(Mallick, 2008)
Cure Shrinkage (%)	5 - 12	(Mallick, 2008)

Table 15. General Mechanical Properties of Polyester

02.2.3. Polyurethanes

Polyurethane [PU] is one of the most versatile classes of polymeric materials known today. Wide variety of structural changes can be produced with the different hydroxyl compounds and isocyanates leading to a wide spectrum of properties and applications (Yeganeh et.al., 2007). High toughness, excellent wear and tear properties and good oil resistance are among the advantages displayed by PUE.

Properties	Value	Reference
Density (g.cm3)	1.24	(Zafar, et al., 2012)
Tensile Strength (MPa)	20.7	(Zafar, et al., 2012)
Tensile Modulus (GPa)	2.8	(Zafar, et al., 2012)
Elongation at Break (%)	8	(Zafar, et al., 2012)

Table 16. General Mechanical Properties of Polyurethane

02.3. Bio-Based Matrix

Advances in petroleum-based fuels and polymers have benefited mankind in numerous ways. Petroleum-based plastics can be disposable and highly durable, depending on their composition and specific application. However, petroleum resources are finite, and prices are likely to continue to rise in the future. In addition, global warming, caused in part by carbon dioxide

released by the process of fossil fuel combustion, has become an increasingly important problem, and the disposal of items made of petroleum-based plastics, such as fast-food utensils, packaging containers, and trash bags, also creates an environmental problem. Petroleum-based or synthetic solvents and chemicals are also contributing to poor air quality. It is necessary to find new ways to secure sustainable world development. Renewable biomaterials that can be used for both bioenergy and bioproducts are a possible alternative to petroleum-based and synthetic products.

This chapter focuses on bio-based polymers derived from plant-based renewable resources, their market potential, and the sustainability of the agriculture industry of the future. The three major plant-based polymers are protein, oil, and carbohydrates. Starch and cellulose, also called polysaccharides, are the main naturally occurring polymers in the large carbohydrate family, (Wool, et al., 2005).

The interest in developing bio-products (bio-based fuels, chemicals, and materials) has been intensified by the fast depletion of petroleum, new environmental regulations, and the growing awareness of global environmental issues and sustainability. Today, most of the chemicals and materials (polymers) are derived from petroleum. At the current rate of consumption, within 50 years, reserves are projected to run out. Therefore, bio-based polymers derived from renewable sources may take over in the plastic and polymer market.

Some of the advantages of using natural components of bio feedstocks are:

1- Minimization of reaction steps and hence waste generation

2- Marketing superiority for biomass products over petroleum-based products

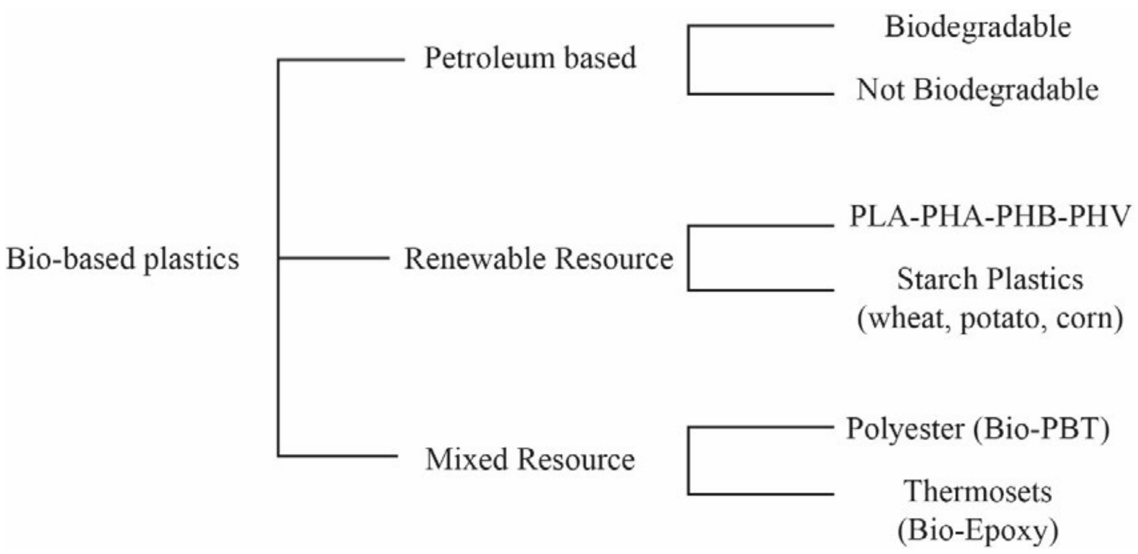


Figure 12. Bio Based Plastics Diagram

02.3.1. Biodegradable Polymers:

A biodegradable polymer is a hydrolysable material. Aliphatic polyesters, and polyolefins possess such desirable properties. Polylactide (PLA) has been proven to be the most attractive and widely used biodegradable polymer, (Rydz, et al., 2015).

02.3.2. Bio-phenolic resins:

Phenol-Formaldehyde (PF), known for its excellent mechanical property, thermal stability, and chemical resistance. Efforts has been made to put in use a new bio-based phenolic product. Lignin offered great promise as a renewable source of phenolic compounds via various thermochemical conversion processes.

Phenolic resin is also useful as binders in friction materials, again thanks to its high heat tolerance. Phenolics resins are widely used in the manufacturing of oriented strand board—a wooden board similar to particle board in that it’s made by adding adhesives and compressing layers of wood stranders in specific orientations, hence the name, (Ismail, et al., 2021).

Phenolic resins are, unfortunately, pretty brittle. For this reason, the majority of phenolic resin applications must include fillers to bolster the resin’s integrity. To do this, the resin and filler material is most commonly compression-molded, but can also be injection or transfer-molded resin as well. Different fillers improve different aspects of the phenolic resin. For example,

cotton improves impact strength, while glass and mineral fillers further improved the heat resistance and stiffness of the resin. The processing time for these thermoset polymers typically takes longer than thermoplastics because of the exothermic chemical reaction that takes place, rather than the polymer hardening simply through cooling, (Subramanian, 2015).

Properties	Value	Reference
Density (g.cm3)	1.213	(Subramanian, 2015)
TensileStrength (MPa)	32	(Subramanian, 2015)
Tensile Modulus (MPa)	5100	(Subramanian, 2015)
Flexural Strength (MPa)	70	(Subramanian, 2015)
Flexural Modulus (MPa)	5600	(Subramanian, 2015)
Impact Resist (J/m2)	15	(Subramanian, 2015)
Glass Temperature	50-70	(Subramanian, 2015)
Td (C)	220	(Subramanian, 2015)
Color	Yellow to dark red	(Subramanian, 2015)

Table 17. General Mechanical Properties of Bio-Phenolic Resins

02.3.3. Bio-based Polyepoxides resins

In order to synthesize bio-based epoxy resin, various renewable resources such as vegetable oil, lignin, fatty acid and cellulose have been used as feedstocks. Soybean oil, linseed oil, or palm oil can be epoxidized by the epoxidation of double bonds with active oxygen, such as with hydrogen peroxide or peracid. The epoxidized oils can then be converted into polymer networks directly by curing with an anhydride as curing agent, or polymerization initiated with a thermally latent catalyst. synthesized bio-based epoxy resins using Biolignin derived from wheat straw as a substitute for bis phenol-A. The wheat straw-derived lignin was epoxidized with polyethylene glycol diglycidyl ether (PEGDGE) rather than epichlorohydrin in alkaline aqueous media, (Lau, et al., 2011).

02.3.4. Bio-Polyester:

Compared with other types of plastics, polyester have greater biodegradability. Usually, Aliphatic polyesters can be prepared by the copolymerization or homopolymerization of cyclic monomers (Scheme 8.3). Bio-polyesters, such as poly (L-lactic acid) (PLA), poly(hydroxybutyrate) (PHB), and other poly (hydroxalkanoates), can be produced by bacteria and are fully biodegradable to produce water, carbon dioxide, and humus, (Lau, et al., 2017).

	Tensile Strength (MPa)	Elongation at Break (%)	Hardness (A)	Tensile Modulus (Mpa)	Reference
Bio Polyester	35	2.5	75	2800	(Mohanty, et al., 2005)

Table 19. Bio Polyester General Mechanical Properties

02.3.5. Bio-polyolefins:

Bio-polyolefins were synthesized with bio-based feedstocks. A bio-composite of high-density polyethylene (HDPE) was produced from sugarcane ethanol and lignocellulosic curaua fibers. To make them biodegradable, natural polymers, such as starch, were added into polyethylene. For example, biodegradable starch-LDPE films containing 30% starch were produced. Targeting structural applications, the properties of a fully bio-based polyethylene composite were tested, in which a bio polyethylene was obtained from sugarcane ethanol. Physical, mechanical, and thermal properties, water uptake, and fracture morphology of the bio composites were evaluated. Compared to the neat bio polyethylene, bio composites

reinforced by various natural fillers resulted in a lower density, increased stiffness, improved resistance to deformation, and better heat resistance. From 2010, on a commercial scale, the first companies for the production of bio-PE have been the Brazilian company Braskem for food packaging, cosmetics, personal care, automotive and toys. Dow is the second largest chemical manufacturer in the world, (Lau, et al., 2017).

03. Composite Manufacturing Techniques

03.1. Hand lay-up technique

This is the simplest and widely used for many years way for the composite formation, especially for large size composites, such as in the boat manufacturing. The reinforcement in this case will be in the form of mat of woven, knitted, or nonwoven. The short fibers or yarns require efforts to get uniform thickness of the formed preform. The thermosetting resin is used and the impregnation of the reinforcement is carried out manually using roller brush to distribute the resin on the surface of the reinforcement and apply enough pressure to allow the resin to penetrate through the reinforcement without voids. The preform may consist of several laminates, so the process will be repeated layer by layer. Resin used may be epoxy, polyester, vinyl ester, and phenolic. However, the quality of the preform depends on the skills of the labor. Due to the high fiber volume ratio, the probability of void formation increases. In order to reduce these risks, a vacuum bag is used to suck the air from the unreachable spaces, helping the resin to reach them. Hand lay or open mold technique is also connected with feeding of the fibers which are cut into small length, may reach micro size, mixed with the polymer and sprayed in the open mold, (El Messiry, 2017).

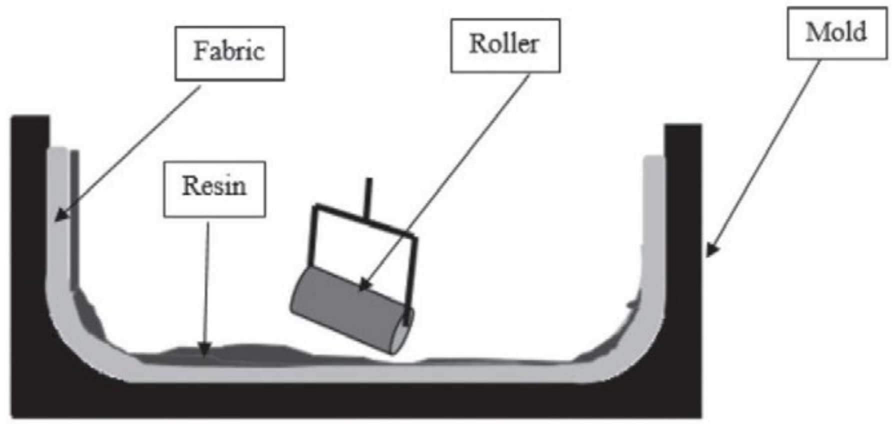


Figure 13. Hand Lay Up Technique (El Messiry, 2017)

03.2. Vacuum bagging technique

Vacuum bag molding uses a flexible film made of a material such as nylon polyethylene or polyvinyl alcohol (PVA) to enclose and seal the part from the outside air. Many times, the vacuum bag molding technique is performed with the assistance of the hand lay-up technique. Laminate is first made by using the hand lay-up technique, and then after it is placed between the vacuum bag and the mold to ensure fair infusion of fibers into the matrix material. The air between the mold and the vacuum bag are then drawn out by a vacuum pump while atmospheric pressure compresses the part. The process can be well understood. Hierarchical composites were prepared with multiscale reinforcements of carbon fibers using a vacuum bagging process, which eliminated chances of detectable porosity and improper impregnation of dual reinforcements, with increases in flexural and interlaminar shear properties by 15% and 18%, respectively, (Rajak, et al., 2019).

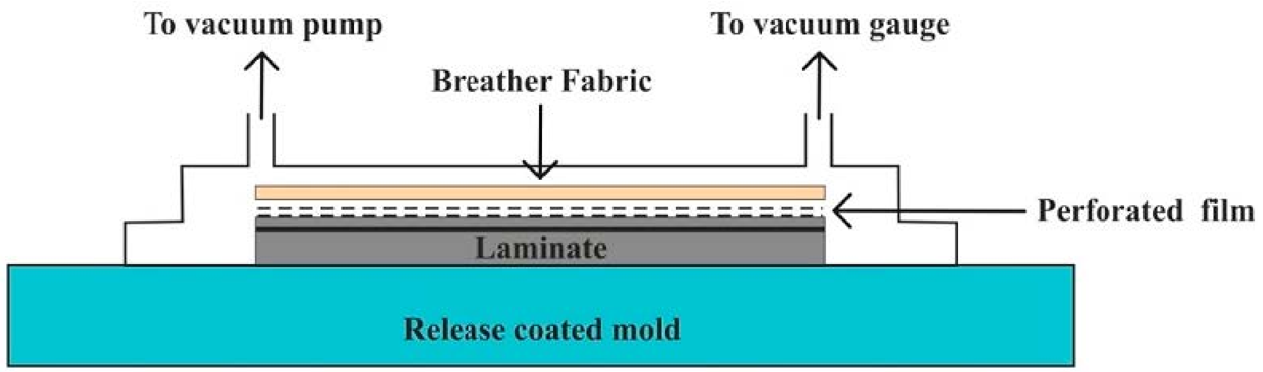


Figure 14. Vacuum Bagging Technique (Rajak, et al., 2019)

03.3. Spray up technique

Spray-up technique is no different than hand lay-up. However, it uses a handgun that sprays resin and chopped fibers on a mold. Simultaneously, a roller is used to fuse these fibers into the matrix material. It is an open mold type of technique, where chopped fibers provide good conformability and quite faster than hand lay-up, (Rajak, et al., 2019).

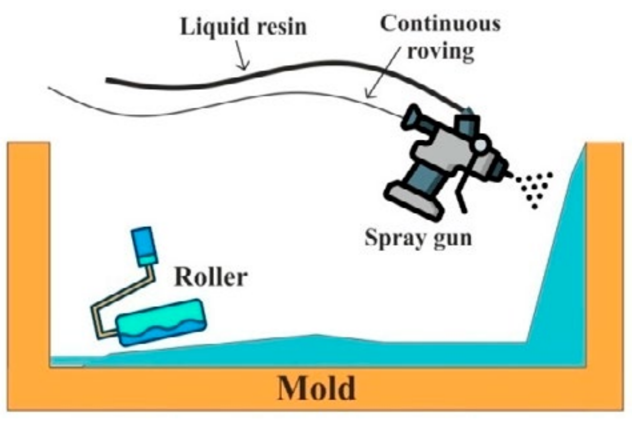


Figure 14B. Spray Up Technique (Rajak, et al., 2019)

03.4. Vacuum infusion technique

It is also called by its patented name SCRIMP, which is performed by flowing the resin through the reinforcement placed on an open mold with the help of a vacuum pressure that also creates a pressure on the layers by the pushing of the membrane called vacuum bag, (Seydibeyoglu, et al., 2017).

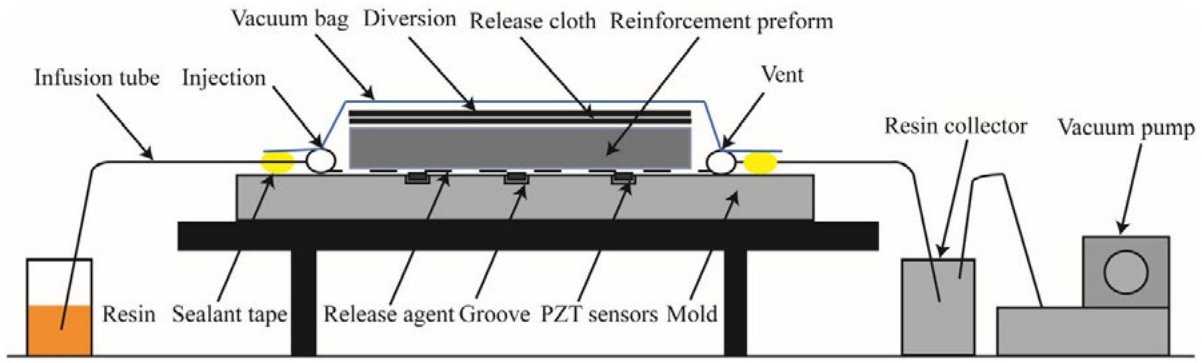


Figure 15. Vacuum Infusion Technique (Seydibeyoglu, et al., 2017)

03.5. Autoclave

Autoclave is one of the most traditional manufacturing methods used in fiber reinforced composite. Until today, it is the only method to cure thermoset materials in order to ensure low level of porosity. It is considered an expensive process due to the unique pressure that autoclave generates. This production method uses the same setup as in vacuum bagging, but additionally a pressure is applied onto the enclosing membrane inside a closed chamber called autoclave which can also provide controlled cooling of the part. High quality parts in terms of mechanical performance can be manufactured by this technique, (Seydibeyoglu, et al., 2017).

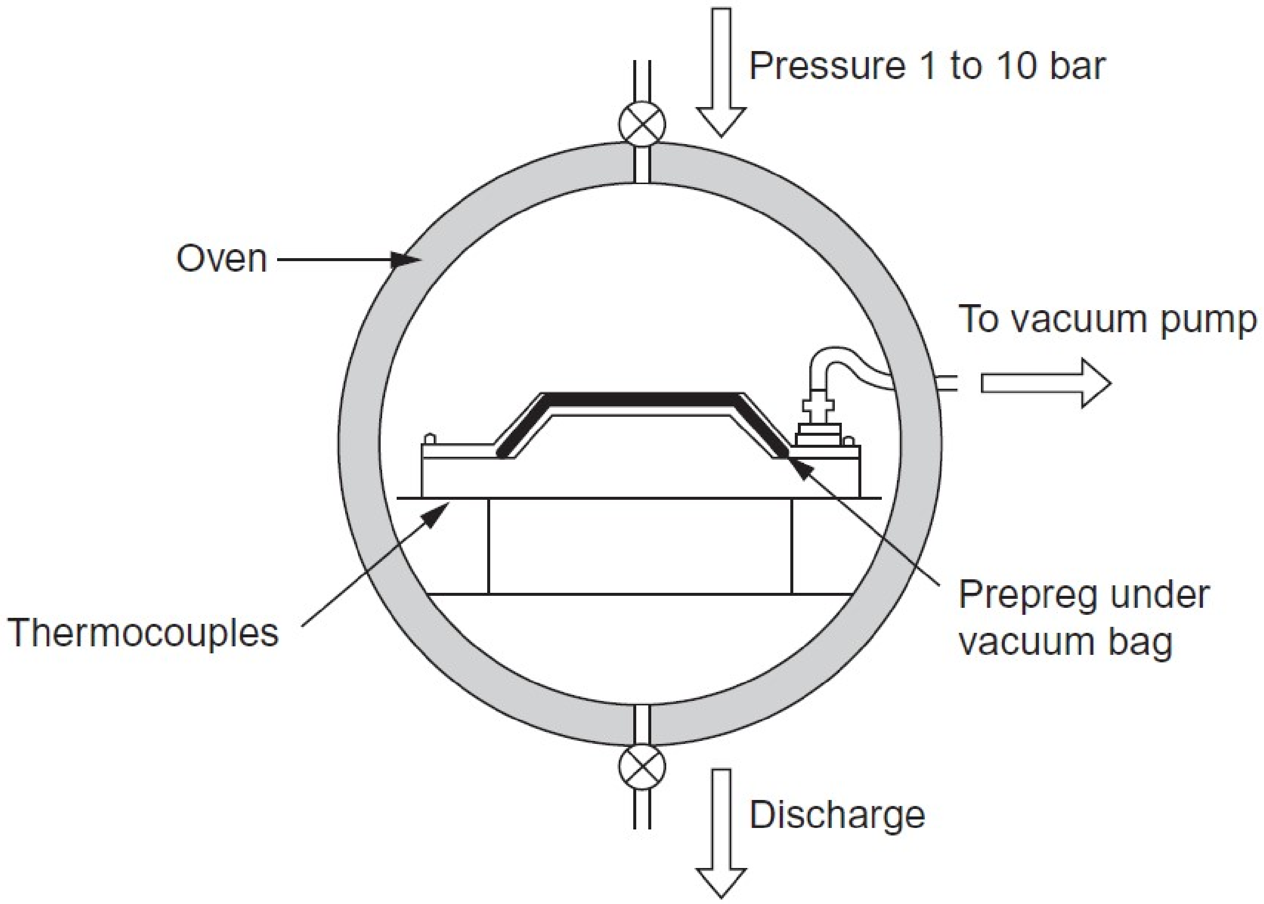


Figure 16. Autoclave Technique (Seydibeyoglu, et al., 2017)

03.6. Pultrusion

The fiber reinforcement may be in the form of continuous yarns wound on packages or fabric or both types. The required number of the yarns to form the reinforcement are fixed on creel and arranged to form a horizontal sheet of yarns at the entrance of the machine. The yarn sheet is pulled through the polymer in Pultrusion tank, where the polymer will be infused into the yarn sheet that passes through the preform die which defines the thickness and width of the composite material. The preform will be subjected to heat in the heated die in order to cure the composite. The composite material will move using a transporting belt and wound at the end of the machine. In multi-layer laminate, fabric can be fed on special creel and passed through the same parts of the machine with the yarn sheet, (El Messiry, 2017).

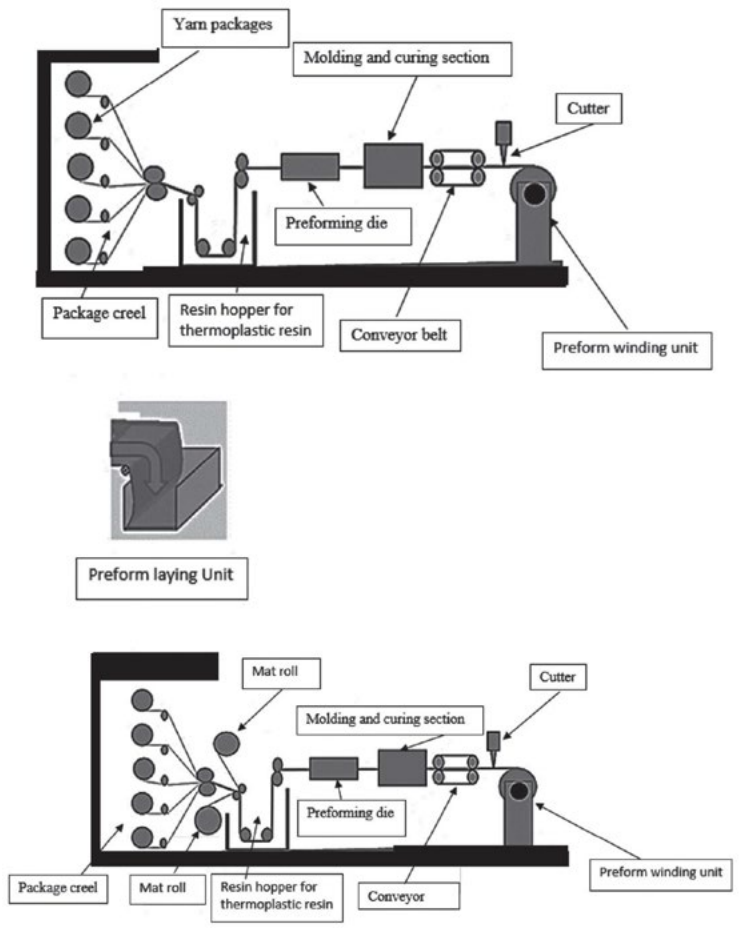


Figure 17. Pultrusion Technique (El Messiry, 2017)

03.7. Filament Winding

It is the most common method to produce parts with axial symmetry. The fibers are impregnated by passing through the resin bath and then wound on a mandrel having a diameter value appropriate to achieve the required part dimension. The resin bath is attached to a transversely traveling head, whose speed arranges the winding angle of the fibers. Cylindrical tanks and large pipes are especially produced by this method, (Seydibeyoglu, et al., 2017).

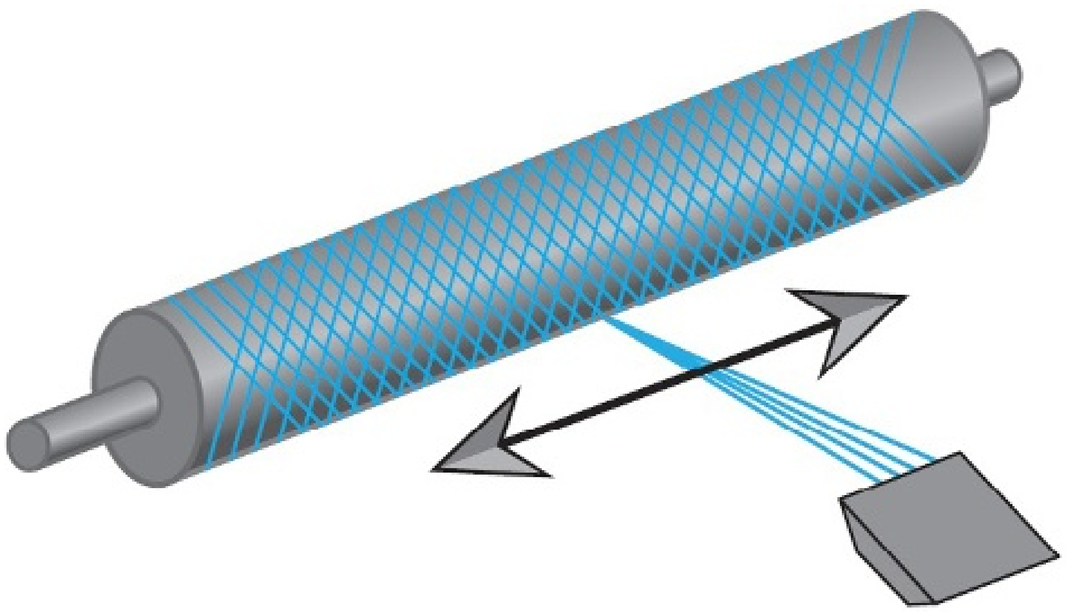


Figure 18. Filament Winding Technique (Seydibeyoglu, et al., 2017)

03.8. Bulk molding compound (BMC)/Sheet molding compound (SMC) technique

Compression molding is one of the widespread production methods, which utilizes fibers and matrices, prepregs, sheet molding compounds (SMC), and bulk molding compounds (BMC) as raw materials. The production is done by applying pressure and (if required) heat to molds in which the raw materials are placed. SMC is one of the most common closed compression molding techniques. SMC resin mats are produced from a high-viscosity fiber/resin compound. The viscosity of the fiber/resin compound decreases during further processing in the closed mold under heat and pressure. As a result, the thermosetting resin containing the isotopically dispersed reinforcing fibers flow into the closed mold, where it cures, (Seydibeyoglu, et al., 2017).

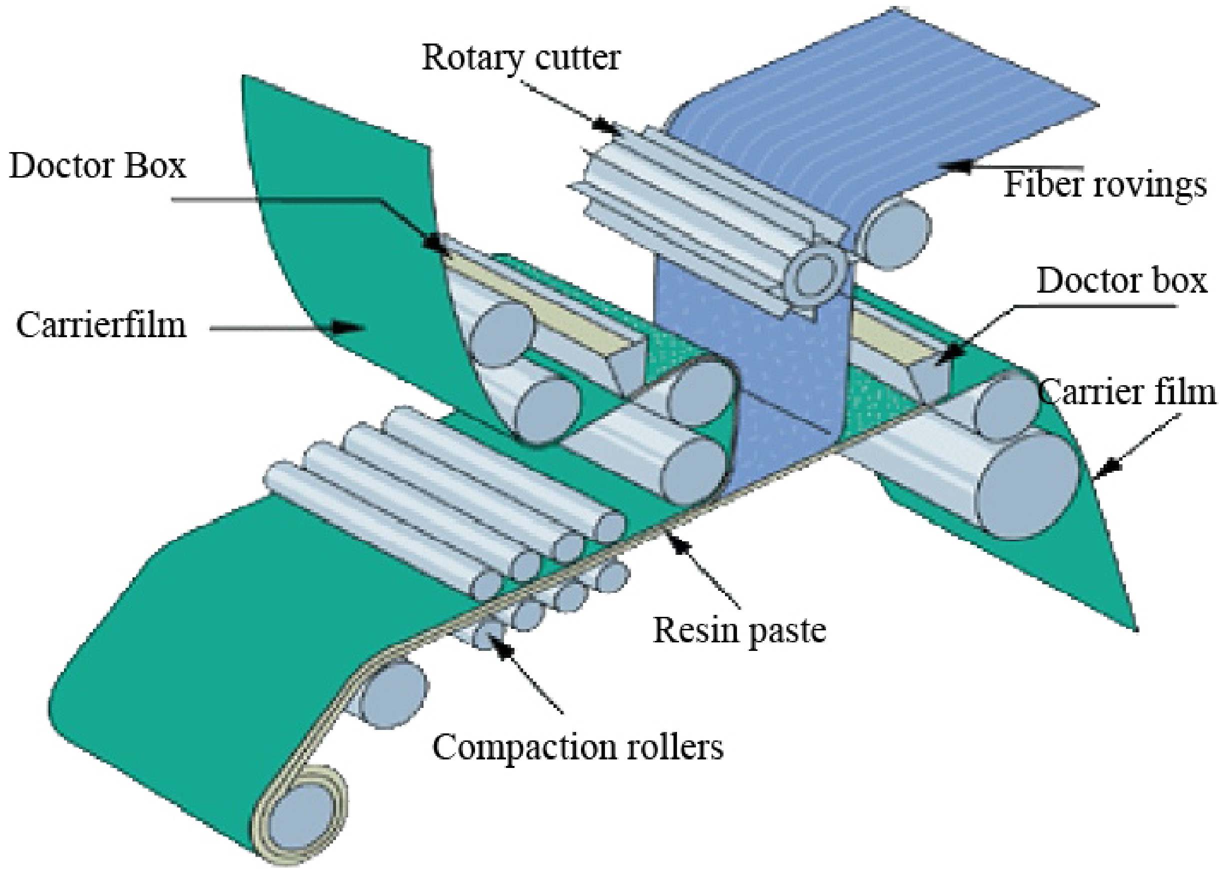
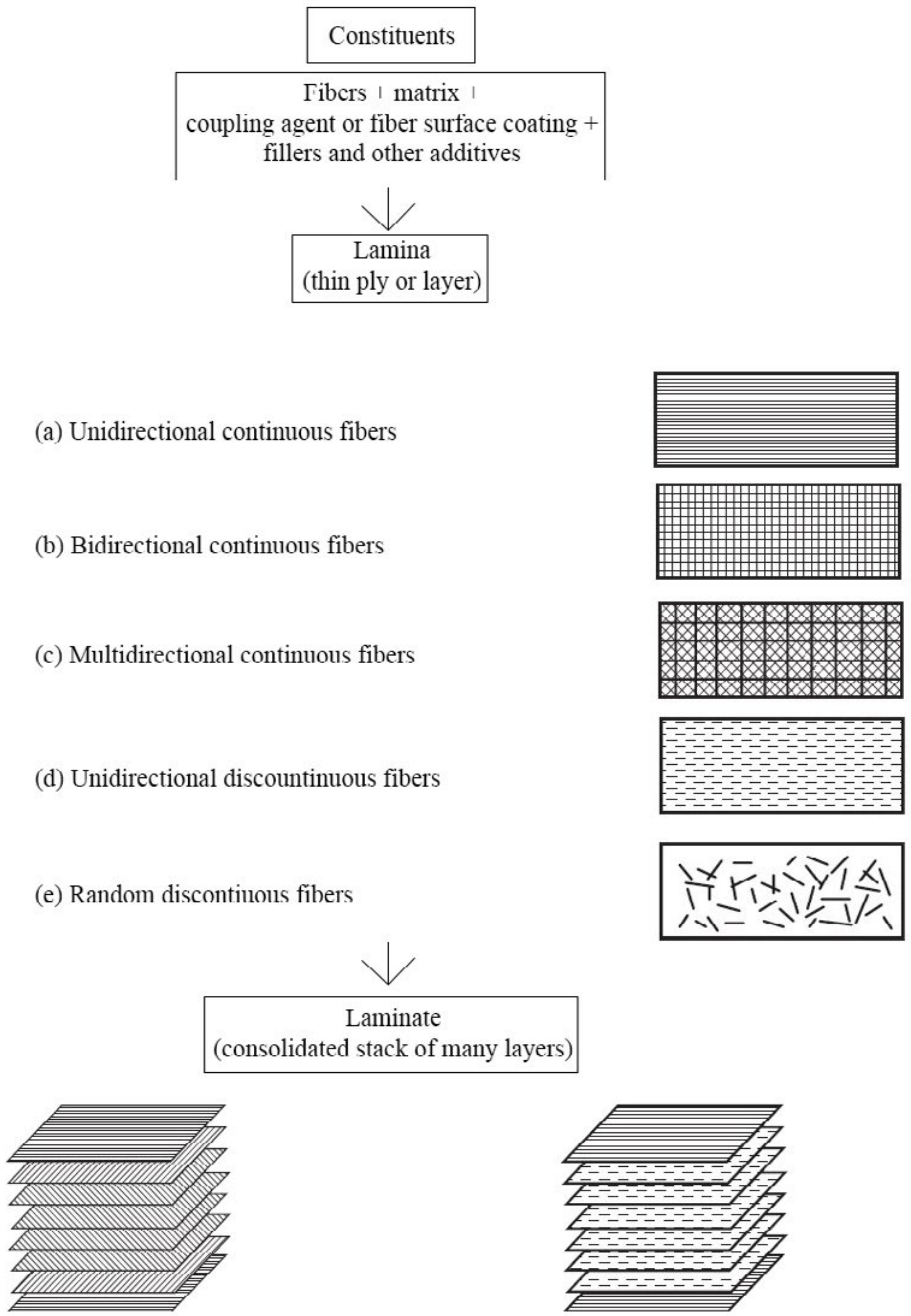


Figure 19. BMC and SMC Technique (Seydibeyoglu, et al., 2017)

04. Composite Engineering & Design

Figure 20. Types of Fibers Composition (Mallick, 2007)



Fibers are the principal constituents in a fiber-reinforced composite material. They occupy the largest volume fraction in a composite laminate and share the major portion of the load acting on a composite structure. Proper selection of the fiber type, fiber volume fraction, fiber length,

and fiber orientation are very important, since it influences the following characteristics of a composite laminate:

1. Density
2. Tensile strength and modulus
3. Compressive strength and modulus
4. Fatigue strength as well as fatigue failure mechanisms
5. Electrical and thermal conductivity
6. Cost

It is important to understand the constituents of a fiber reinforced composite as a whole before going into the details of the fiber architecture that will be discussed in this section, (Fan, et al., 2017).

04.1. Fiber architecture

Fiber architecture is defined as the arrangement of fibers in a composite, which not only influences the properties of the composite, but also its processing. The characteristics of fiber architecture that influence the mechanical properties include:

1- fiber continuity
2- fiber orientation
3- fiber crimping
4- fiber interlocking.

During processing, matrix flow through the fiber architecture determines the void content, fiber wetting, fiber distribution, dry area and others in the final composite, which in turn, also affect its properties and performance, (El Messiry, 2017)

04.1.1. One-dimensional continuous fibers

In the one-dimensional architecture, fiber strands (or yarns) are oriented all in one direction. The unidirectional orientation of continuous fibers in the composite produces the highest strength and modulus in the fiber direction, but much lower strength and modulus in the transverse to the fiber direction. A multilayered composite laminate can be built using the one-dimensional architecture in which each layer may contain unidirectional continuous fibers, but the angle of orientation from layer to layer can be varied. With proper orientation of fibers in various layers, the difference in strength and modulus values in different directions can be reduced. However, one major problem with many multilayered laminates is that their interlaminar properties can be low and they can be prone to early failure by delamination, in which cracks originated at the interface between the layers due to high interlaminar tensile and shear stresses cause separation of layers, (Mallick, 2007).

04.1.2. Two-dimensional continuous fibers

The two-dimensional architecture with continuous fibers can be either bidirectional or multidirectional. In a bidirectional architecture, fiber yarns (or strands) are either woven or interlaced together in two mutually perpendicular directions. These two directions are called warp and fill directions, and represent 0º and 90º orientations, respectively. The fiber yarns are crimped or undulated as they move up and down to form the interlaced structure. By changing the number of fiber yarns per unit width in the warp and fill directions, a variety of properties can be obtained in these two directions. If the number of fiber yarns is the same in both warp and fill directions, then the properties are the same in these two directions and the fabric is balanced. However, the properties in other directions are still low. In order to improve the properties in the other directions, fiber yarns can be interlaced in the other directions to produce multidirectional fabrics.

Knitting and braiding are two other textile processes used for making two-dimensional fiber architecture. In a knitted fabric, the fiber yarns are interloped instead of interlaced. If the knitting yarn runs in the cross-machine direction, the fabric is called the weft knit, and if it runs in the machine direction, it is called the warp knit, (Mallick, 2007).

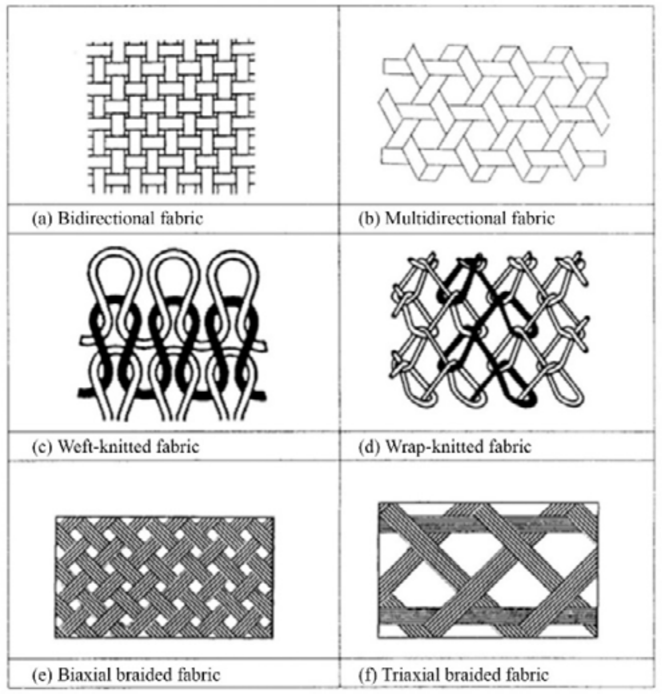


Figure 21. Different Type of Fiber Fabric Compositions (Mallick, 2007)

A two-dimensional architecture can also be created using randomly oriented fibers, either with continuous lengths or with discontinuous lengths. The former is called the continuous fiber mat (CFM), while the latter is called the chopped strand mat (CSM). In a CFM, the continuous yarns can be either straight or oriented in a random swirl pattern. In a CSM, the fiber yarns are discontinuous (chopped) and randomly oriented. In both mats, the fibers are held in place using a thermoplastic binder. Because of the random orientation of fibers, the composite made from either CFM or CSM displays equal or nearly equal properties in all directions in the plane of the composite and thus, can be considered planar isotropic.

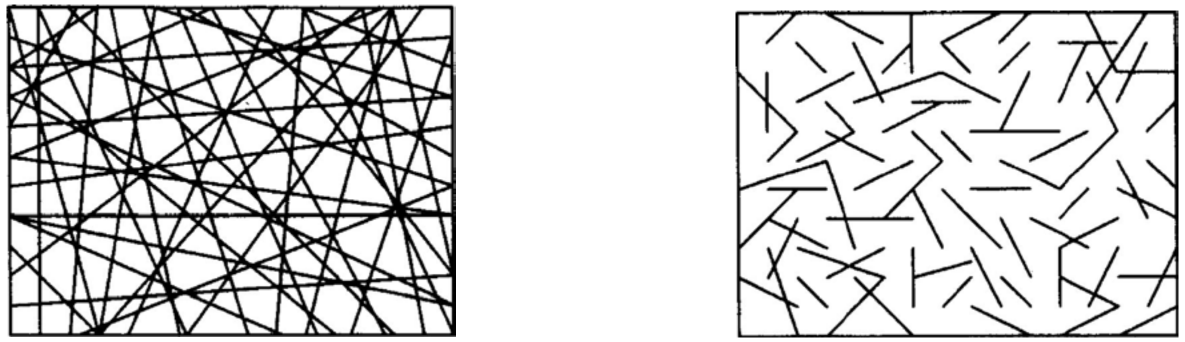


Figure 22. Random Oriented Fibers. On the left CFM, On the right CSM (Mallick, 2007)

04.1.3. Three-dimensional continuous fibers

Composites made with one and two-dimensional fiber architectures are weak in the z-direction (thickness direction) and often fail by delamination. To improve the interlaminar properties, fibers are added in the thickness direction, creating a three-dimensional architecture.

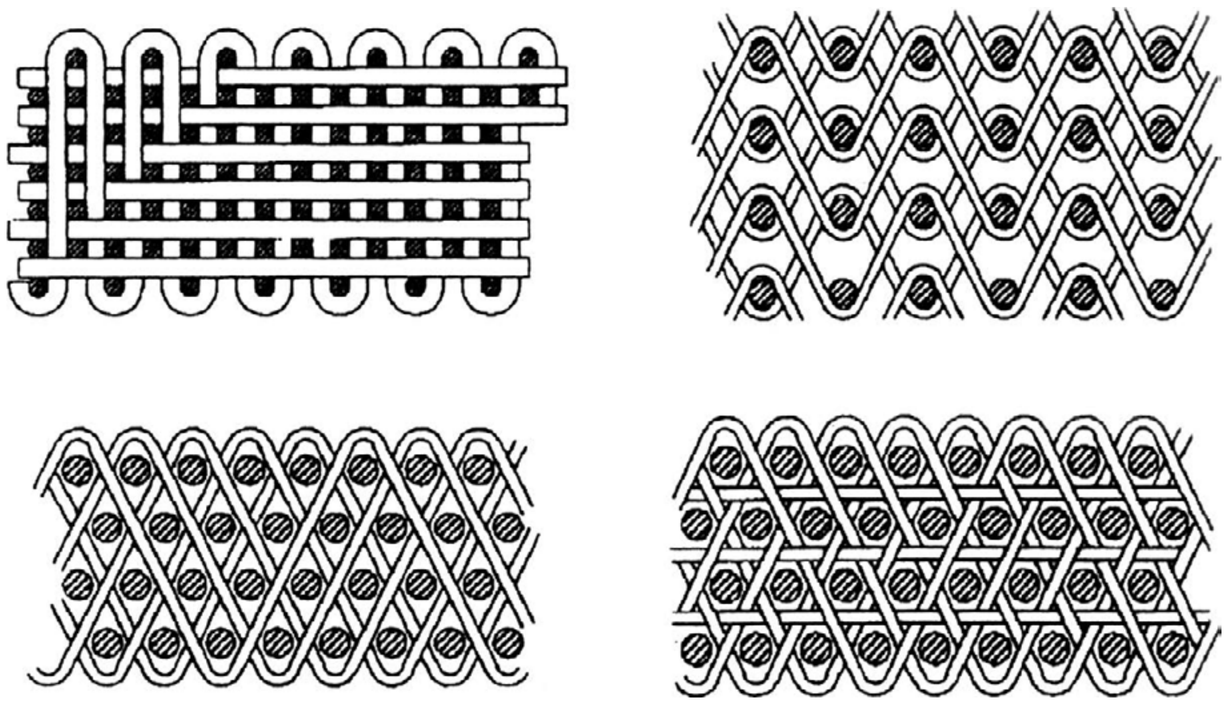


Figure 23. Three-Dimensional Continuous Fibers Composition (Mallick, 2007)

III – Literature Interpretation & Conclusions

01. Fiber Selection

Following the literature review findings, the choice of the fibers and resin to be used in the panel fabrication and the testing was made by checking several important factors:

1) Choosing the physical and mechanical properties of the fiber itself.

Physical	Mechanical
Length	Stiffness
Density	Tensile Strength
Moisture Absorption	Fatigue Strength

Table 22. Physical & Mechanical Properties to be considered

2) Checking the availability, and the cost of the chosen fiber.

	Density (g/cm3)	Moisture Content (%)	Tensile Strength (MPa)	Stiffness (GPa)	Availabilty	Cost (sqm)
Hemp	1.5	6	750	70	No	-
Jute	1.3	9	600	20	Yes	12
Flax	1.5	8	500	27	Yes	17

Table 23. Comparison between Flax/Jute/Hemp

As a result of the comparison done in table 3 (Chap 01.6), Flax and Jute showed very close results. However, an important aspect led to choose Flax instead of Jute which is the fiber architecture and arrangements. As mentioned in previous chapter 5, the fiber arrangements can affect strongly the mechanical properties of the composite. The advantage of Flax over Jute was its availability in several arrangements, it means that there are several end results to be compared. This is not the case for jute that is available only as bidirectional: 1 wrap x 1 fill is available for Jute.

Flax could be found Unidirectional rolls, stitched rolls (2 wrap x 1 fill / 3wrap x 2 fills/…)

Figure 24. Flax Fiber Types

Analyzing previous research papers using Flax as a reinforcement material, facilitated the choice of flax fiber arrangement for this study. According to Oksman (2008) Unidirectional Flax Fiber and Cross Stitched are the commonly used ones due to their good reaction with the resin, easy for formability and placing in mold. Therefore, two type of flax fiber arrangement were chosen:

- 200g/sqm Unidirectional Flax Fiber Tape. 180.
- 180 g/sqm Cross-Stitched Unidirectional Flax Fiber.
-

Figure 25. Unidirectional Flax Fiber (right) – Cross Stitched Flax Fiber (left)

02. Resin Selection

The aim of this study is to fabricate a composite that is predominated by Bio-Based products and materials. Analyzing the findings of the literature (chapter of resin) shows that the advances in the field of bio-based polymer products is still slow especially when it comes to the products available to buy by consumers. Only few companies are selling bio-based polymers and it will always stay partially petrol-based. Examples of the companies selling these products are:

Production of Bio-based Polymers	Product Focus	Bio-Base Content
Cardolite – Belgium - https://www.cardolite.com/	Epoxy	36 %
Scabro – Netherlands - https://www.scabro.com/	Epoxy	40 %
Sicomin – France - http://sicomin.com/	Epoxy	56 %
Braskem – Brazil&Netherlands - https://www.braskem.com.br/	PE	100%

Table 24. Available Bio-Based Epoxies in the Netherlands

Since the manufacturing technique to be used is either hand lay-up, vacuum bagging, or vacuum assisted resin infusion, the only possible option for these processes is epoxy, and to achieve a higher bio-based content the product from Sicomin was chosen with a bio-based content of 56%.

The product “Résine époxy SR GreenPoxy 56” comes in a liquid state and transparent. It has a viscosity of 1600 mPa.s at a temperature of 20 C. At this temperature the product has a density of 1.198 g/cm3.

Figure 26. Bio-Epoxy Used in fabrication

Epoxy can never be used on its own, for that a hardener is always required. The hardener that was used for this research is SD 7561 available at Sicomin. The hardener when mixed with Epoxy lead to the transformation of the Epoxy from a liquid state to a solid state in a specific amount of time. SD 7561 is considered to have a slow reaction time, and this is one of the main reasons it was chosen. It gives the manufacturer more time to fix any issue in fabrication before the resin cures, in other words, the epoxy becomes in a solid state. The epoxy to hardener ratio is recommended on by the company to be 100g of epoxy to 36g of hardener.

03. Fabrication Process Selection

The sample fabrication took place in TU Delft Lab, under the supervision of Hans. Following the findings of the literature, Hand Lay-Up, Vacuum Bagging, & Vacuum Assisted Resin Transfer Molding are the only techniques that could be done without the use of heavy machinery, or professional composite fabrication tools such as extruders, winding machines, compression machines, and others. To choose a suitable manufacturing technique between Hand Lay-Up, Vacuum Bagging, & Vacuum Assisted Resin Infusion (VARTM), a comparison between the advantages and disadvantages of each one of these manufacturing techniques was elaborated in the following table 25 and furtherly summarized in table 26

Fabrication Method	Advantages	Disadvantages
Hand Lay-Up	Control over the amount of epoxy in the composite Faster Curing Time Cheaper Tooling Cost Could be used for very large parts No waste consumables	Depends strongly on labor skills Longer time to apply the epoxy of the fibers Air cannot be completely removed from the composite Flaws in the surface due to uneven roller pressure
Vacuum Bagging	Air can be totally withdrawn using the pump Unformal pressure applied in all directions leading to a consolidated part	Generate Waste Consumables Longer Curing Time Provide only a good surface finish on 1 side. Depends Strongly on labor skills Expensive tooling
Vacuum Assisted Resin Transfer	Consist resin usage Cleaner Process Minimize styrene emissions due to resin curing in closed environment Minimal to no voids in the finished laminate Uniform Distribution of fibers and epoxy along the whole composite. Slow Injection making sure every single fiber is absorbing the required amount of epoxy. Faster Fabrication Labor cost reduced Stronger outcome	Issues with air leak can cause the failure of the whole laminate Once the process starts, no changes or modifications can be done Generation of a large amount of waste (pipes, Nylon Plies, Infusion Mesh, Tape, Sealing Bag) Not cost effective at high volumes

Table 25. Comparison between Advantages and Disadvantages of Hand Lay-Up, Vacuum Bagging, and VARTM

Aspects	Hand Lay-Up	Vacuum Bagging	Vacuum Assisted Resin Infusion
Time Efficiency	-	+	++
Labor Consumption	Too much	Too much	Very few
Cost	€	€€	€€€
Uniformity	-	+	++
Waste Generation	No waste	Few Waste	Lots of Waste
Finishing	-	+	++

Table 26. Comparison between Hand Lay-Up, Vacuum Bagging, and VARTM

It is a priority for the testing of the material to have a uniform surface of the panel and a good distribution of epoxy among all the composite. Following the comparison that was done between the manufacturing processes, Vacuum Assisted Resin Transfer Molding will greatly reduce the error margin and the defects in the final outcome. It will also provide a uniform distribution of epoxy among the panel. For that it is the most suitable for this research.

IV- Research by Experimentation

01. Equipment (Appendix)

02. Fabrication: VARTM

The diagram below represents the basic understanding of the manufacturing process, it also shows the location of each specific item needed to perform this process.

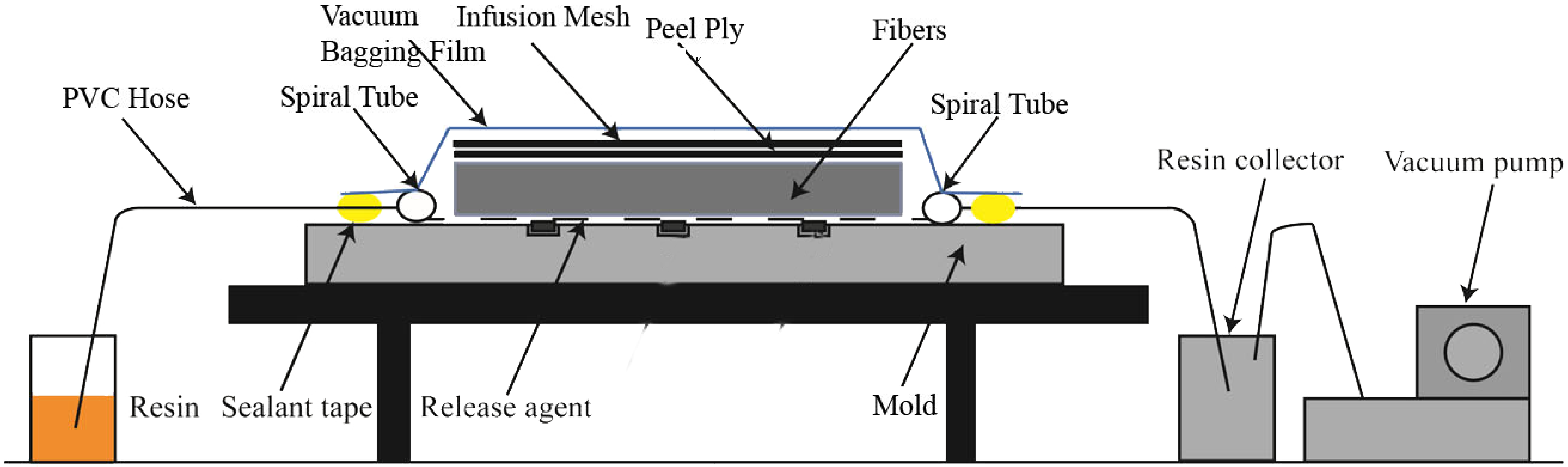


Figure 28. VARTM Fabrication Process

Process Steps and remarks

1- Choose the surface of the mold (plastic, wood, glass, metal). The choice of the surface of the mold has an impact on the finishing of the product.

2- Apply the wax on the surface of the mold following the instructions on the product (this might take up to 1 to 1.5 hours)

3- Cut the Vacuum Bagging Film PP180, Peel Ply Black, the FM100 Infusion Mesh, and the fibers to required size. Fibers must be 1.5cm smaller than the peel ply and the FM100 Infusion Mesh. The peel ply black and the Infusion mesh should be 1.5cm smaller than the Vacuum Bagging Film.

4- Place the resin feed spirals, the resin infusion connector.

5- Seal everything and apply pressure on edges to make sure there is no air leak

6- Connect the inlet to an empty pot using the PVC Vacuum Hose, and the outlet to the resin catch pot

7- Connect the resin catch pot to the vacuum pump.

8- test the system several times to make sure that there is 0 air leak

9- Mix the epoxy and the hardener and start the process.

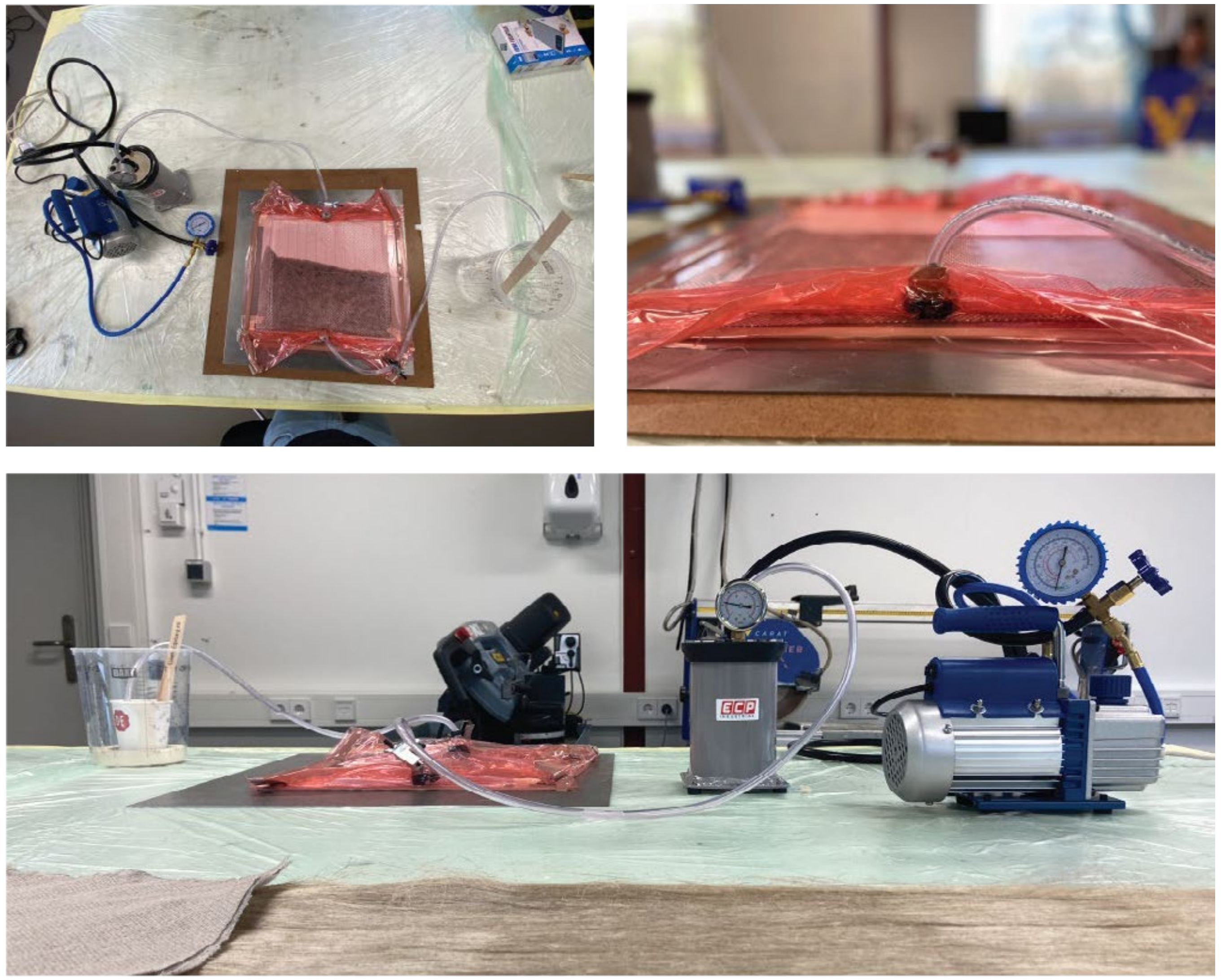


Figure 28. Fabrication VARTM at TU Delft

An interesting finding during the process is that the surface of the mold has a direct effect on the final finish of the composite panel. In other words, the surface of the composite will copy the surface of the mold in its aspects. If the mold is a mirror glass, the composite finish surface will have a glossy reflective finish. If the mold is mat steel, the finish surface of the composite will have a smooth mat finish. And finally, is the mold was wooden, the final surface of the composite will have a texture similar to the wood.

03. Panels Composition

3 scenarios were decided on to be tested for this research. The first one (F2) is a simple 2 layers of unidirectional Flax Tape positioned in the same direction (0°, 0°). This sample is to be tested in the same direction of the fibers. The second scenario (F4) is sample with 4 layers of Unidirectional Flax Tape placed in 2 directions symmetrically, therefore (0°, 90°, 90°, 0°). The test is to be done in the direction of the first layer, therefore the direction of the fibers (0°). The third scenario (F'6) is a combination of 6 layers of Cross-stitched Unidirectional Flax positioned in a symmetrical order of (0°, 90°, 45°,45°, 90°, 0°). The test is to be done in the direction 0°. F''6 and F'6 are exactly the same samples, however during the fabrication of F''6, the panel was removed before complete curing and showed a lot of defects on the surface, for this reason the panel was repeated (Panel F''6). The choice of these three scenarios gives an understanding of the performance of the fibers when they are in the same direction, when they are in perpendicular direction, and when they combine 3 different directions. There are a thousand other scenarios that could be tested to understand more the performance of the material, due to the timeframe of the research, three scenarios were enough

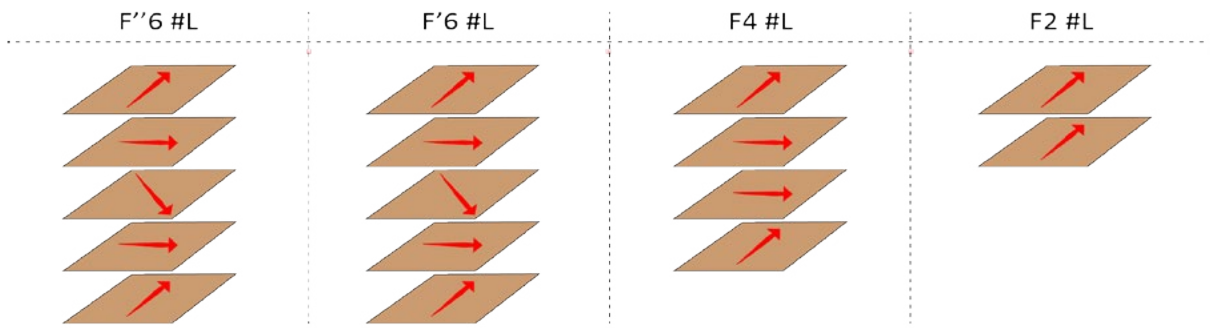


Figure 29. Panel Composition choices

Sample #	F''6	F'6	F4	F2
Preparation Time (mins)	120	120	120	120
Infusion Time (mins)	13	13	9	7
Curing Time (mins)	2400	2400	2400	2400

Table 27. Panel Fabrication Time

05. Hand Lay-Up & VARTM Epoxy/Natural Fiber Composites

Fiber Type	Direction	Number of Plies	Process	Resin	Tensile Strength (Mpa)	Youngs Modulus (MPa)
Unidirectional Flax (180 g/sqm)	0	10	VARTM	Epoxy	265	10300
3x1 weave Flax	0	6	Hand Lay-up	Epoxy	90	1000
Flax Woven Fabric (280g/sqm)	0	8	Vacuum Bagging	Epoxy	90	1800
Unidirectional Flax (150g/sqm)	0, 90, 0, ...	16	Hand Lay-Up	Epoxy	80	3100
Hemp/Jute/Hemp Weave	0	3	hand Lay Up + 25 Kgs Compression	Epoxy	120	1700
Basalt / Flax	0	16	VARTM	Epoxy	298	17000

04. Testing of Panel

The purpose of this research is to check the effect of water, temperature, and UV radiations on the mechanical properties of natural fiber reinforced composites. The focus of this research is on the mechanical properties related to the bending and tension properties of the natural fiber reinforced panel, and for this reason, the panels were designed to be cut into specimens following the standards ISO 527-5:2021(E). "Determination of tensile properties – Test conditions for unidirectional fiber-reinforced plastic composites". & ISO 14125. "Fiber-reinforced plastic composites – Determination of flexural properties". Following the standards, the panels were cut into rectangular specimens of 25 mm x 300 mm. Out of every panel, 15 specimens were produced. Fundamentally, 5 specimens of each panel will be tested for tension, and the 5 others will be tested for bending. The remaining samples will be subjected to UV light, high temperature, and water to be tested again and compared with the original results. All tests were carried out at the Mechanical Engineering Lab at TU Delft under the supervision of Fred Veer.

04.1. Subjection to UV Radiations:

To understand the effect of UV radiations on this material, 8 samples were subjected to a 300W ULTRA VITALUX light bulb in the UV accelerated weathering machine for a period of 4 weeks at TU Delft on Monday 28 March 2022 at 11:30am. Every week of subjection to UV radiations in the above-mentioned machine represents 1 year of exposition to UV radiations in an outdoor environment similar to the conditions in a Dutch environment. In other words:

1 week of UV accelerated weathering machine = 1 year of outdoor conditions (Dutch Climate)

Figure 30. UV Machine

Figure 31. UV Lamp Machine

04.2. Subjection to High Temperature:

High temperature can affect fiber reinforced composites greatly, for that it was important for this research to understand the effect of temperature on some of the physical and mechanical properties of the fibers. 8 samples were placed in Heraeus Oven at the BK-Lab at TU Delft. The samples were subjected to a cycle of 3 phases:

- Phase 1: 45 degrees for 48 hours – cooling till 20 degrees
- Phase 2: 55 degrees for 24 hours – cooling down to 30 degrees
- Phase 3: 65 degrees for 24 hours – cooling down to room temperature.

After this cycle, if the mechanical and physical properties of this material are not highly affected, it is possible to say that the material could resist outdoor high temperatures.

Figure 32. Temperature Machine

04.3. Subjection to Water:

Similar to temperature and UV, water is equally important when subjecting a product to weathering conditions. Especially when the product will be applied in countries that have strong rainy days. Due to the fact that there is no available machine at TU Delft that could accelerate the effect of water on a sample, it was recommended by Barbara Lubelli to do this manually by placing samples in salty water for 7 days while making sure that the water is covering all the front side of samples.

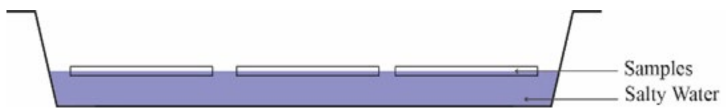


Figure 33. Scheme of Water Subjection Scheme

V- Results: Fabrication & Tests

Panel Name	Fiber Type	Size (mmxmm)	Number of Layers	Orientation (o)	Infusion Time (min)	Epoxy Used	Hardner Used	Epoxy : Hardner Ratio (g)
F2	200g Unidirectional Flax Fiber	295 x 295	2	(0, 0)	7	Sicomin Greepoxy	SD 7561	100:36:00

Table 29: Panel F2 Fabrication Details

Panel	Thickness (mm)	Weight of Fibers (g)	Weight Matrix (g)	Density Fibers (g/cm^3)	Density Matrix (g/cm3)	Volume Fraction Fibers (-)			Volume Fraction Matrix (-)	Density Composite (g/cm^3)	Test Direction
						0°	*90°*	*45°*			
F2	1.2	33	40.5	1.5	1.17	0.39	0	0	0.61	1.3	0

Table 30: Panel F2 Composition details

Panel	Ultimate tensile Strength (MPa)	Standard Deviation of UTS (MPa)	Young's Modulus (MPa)	Standard Deviation of YM's (MPa)	Elongation (%)
F2	197.5	29.7	5601.29	854	3.45
After Water Test	217	34	5204	432	4.15
After UV Test	165	31.5	5826	634	3.45
After Temp Test	234	21.5	6295	468	3.71

Table 31: Panel F2 Mechanical Properties (before & after weathering conditons)

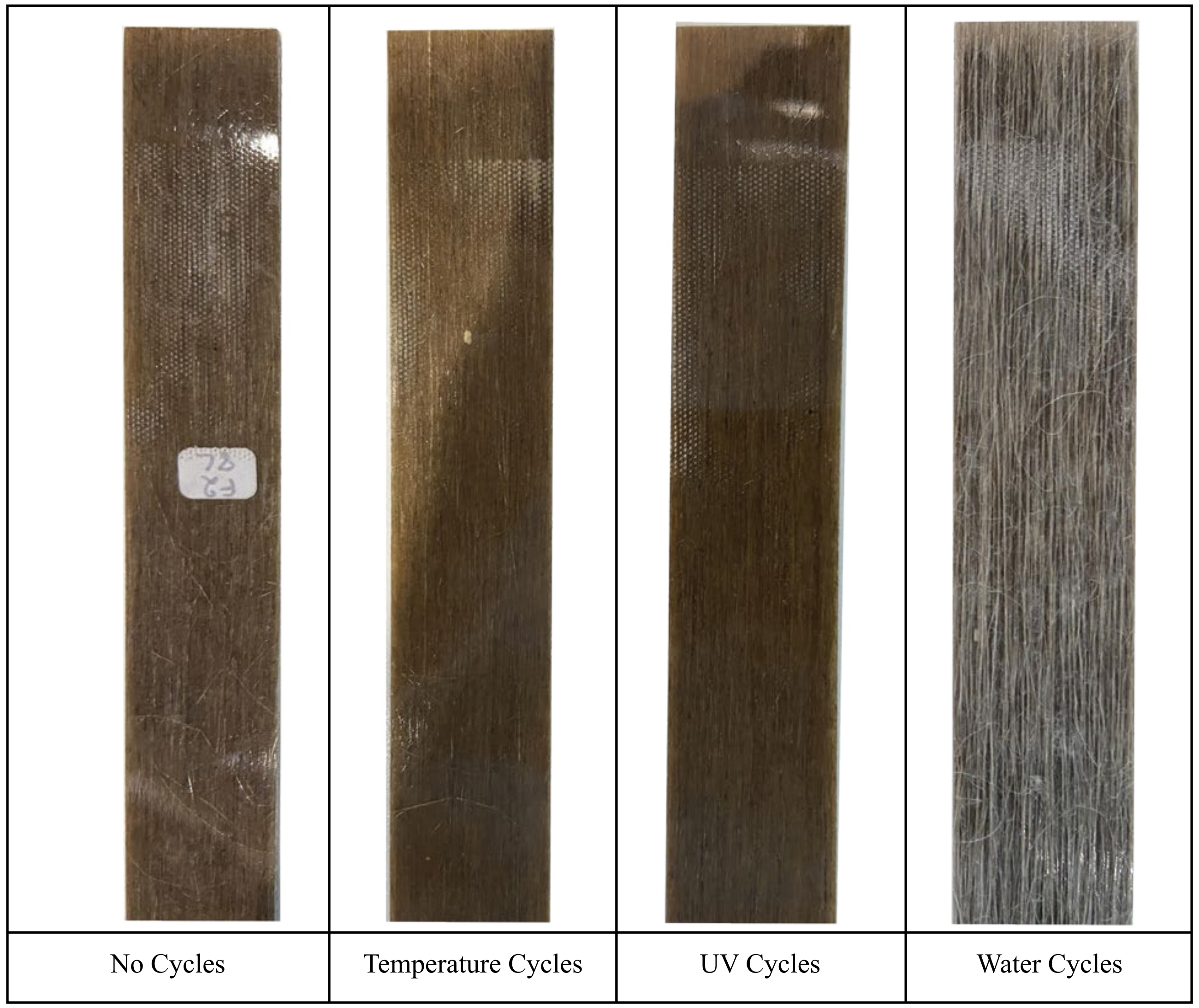


Figure 34: Panel F2 before and after weathering conditions

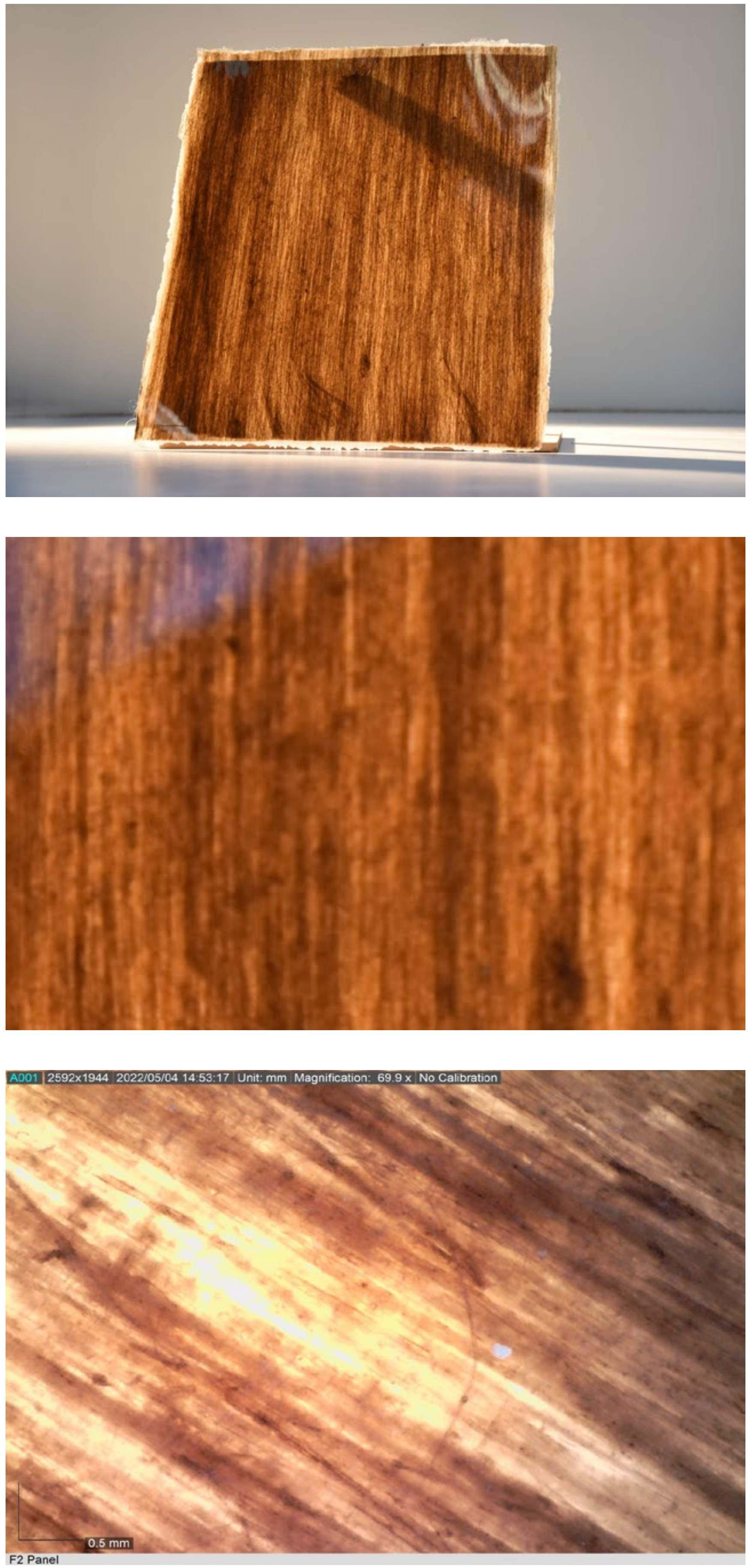


Figure 35: Panel F2 (Top) - Texture of Panel F2 (Mid) - Microscopic Picture (Bot)

Panel Name	Fiber Type	Size (mmxmm)	Number of Layers	Orientation (o)	Infusion Time (min)	Epoxy Used	Hardner Used	Epoxy : Hardner Ratio (g)
F4	200g Unidirectional Flax Fiber	295 x 295	4	(0, 90, 90, 0)	9	Sicomin Greepoxy	SD 7561	100:36:00

Table 32: Panel F4 Fabrication Details

Panel	Thickness (mm)	Weight of Fibers (g)	Weight Matrix (g)	Density Fibers (g/cm^3)	Density Matrix (g/cm3)	Volume Fraction Fibers (-)			Volume Fraction Matrix (-)	Density Composite (g/cm^3)	Test Direction
						0°	*90°*	*45°*			
F4	3	66	81	1.5	1.17	0.195	0.195	0	0.61	1.31	0

Table 33: Panel F4 Composition details

Panel	Ultimate tensile Strength (MPa)	Standard Deviation of UTS (MPa)	Young's Modulus (MPa)	Standard Deviation of YM's (MPa)	Elongation (%)
F4	86.28	8.25	1718.27	121.4	3.61
After Water Test	74	11	1560	118	3.65
After UV Test	96	6	2641	151	3.6
After Temp Test	91	7.46	2324	146	3.9

Table 34: Panel F4 Mechanical Properties (before & after weathering conditons)

No Cycles	Temperature Cycles	UV Cycles	Water Cycles

Figure 36: Panel F4before and after weathering conditions

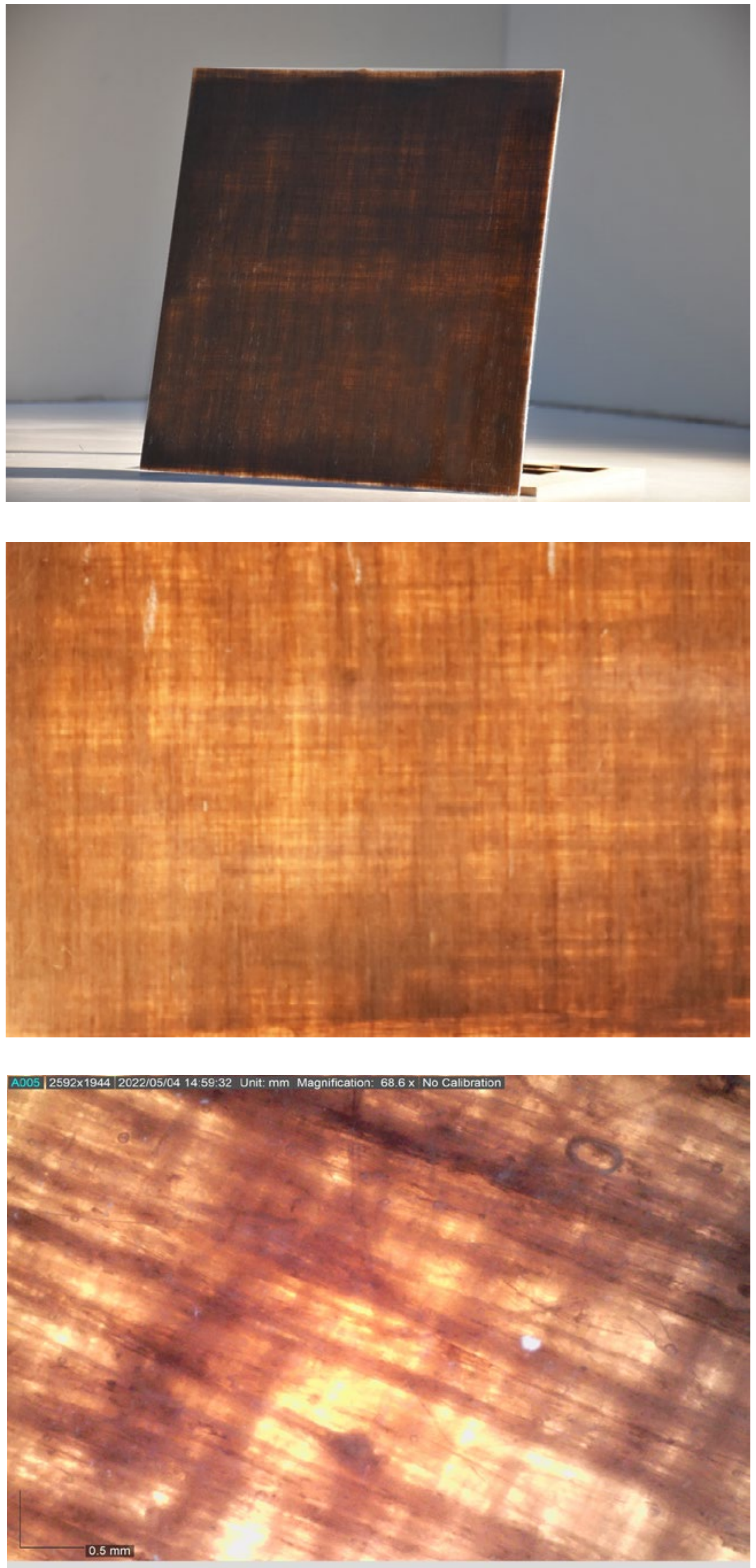


Figure 37: Panel F4 (Top) - Texture of Panel F4 (Mid) - Microscopic Picture (Bot)

Panel Name	Fiber Type	Size (mmxmm)	Number of Layers	Orientation (o)	Infusion Time (min)	Epoxy Used	Hardner Used	Epoxy : Hardner Ratio (g)
F'6	180g Cross Stitched Flax Fiber	300 x 300	6	(0, 90, 45, 45, 90, 0)	13	Sicomin Greepoxy	SD 7561	100:36:00

Table 35: Panel F’6 Fabrication Details

Panel	Thickness (mm)	Weight of Fibers (g)	Weight Matrix (g)	Density Fibers (g/cm^3)	Density Matrix (g/cm3)	Volume Fraction Fibers (-)			Volume Fraction Matrix (-)	Density Composite (g/cm^3)	Test Direction
						0°	*90°*	*45°*			
F'6	2.5	81	100	1.4	1.17	0.16	0.16	0.08	0.6	1.26	90

Table 36: Panel F’6 Composition details

Panel	Ultimate tensile Strength (MPa)	Standard Deviation of UTS (MPa)	Young's Modulus (MPa)	Standard Deviation of YM's (MPa)	Elongation (%)
F'6	86.158	2.72	2087.85	59	3.86
After Water Test	97	4.62	1878	68	5.16
After UV Test	88	4.56	2690	135	3.275
After Temp Test	92	3.56	2753	68	3.54

Table 37: Panel F’6 Mechanical Properties (before & after weathering conditons)

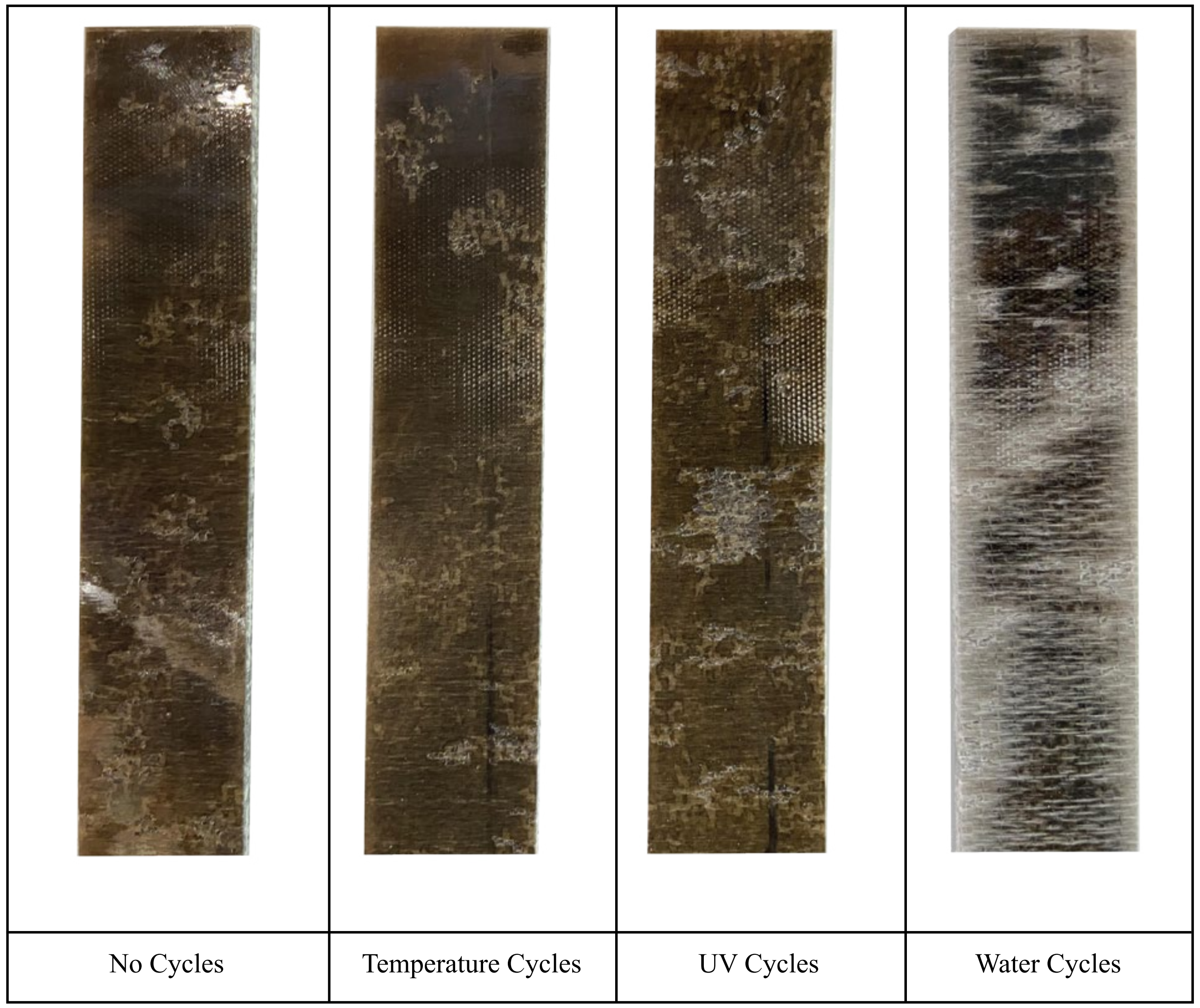


Figure 38: Panel F’6 before and after weathering conditions

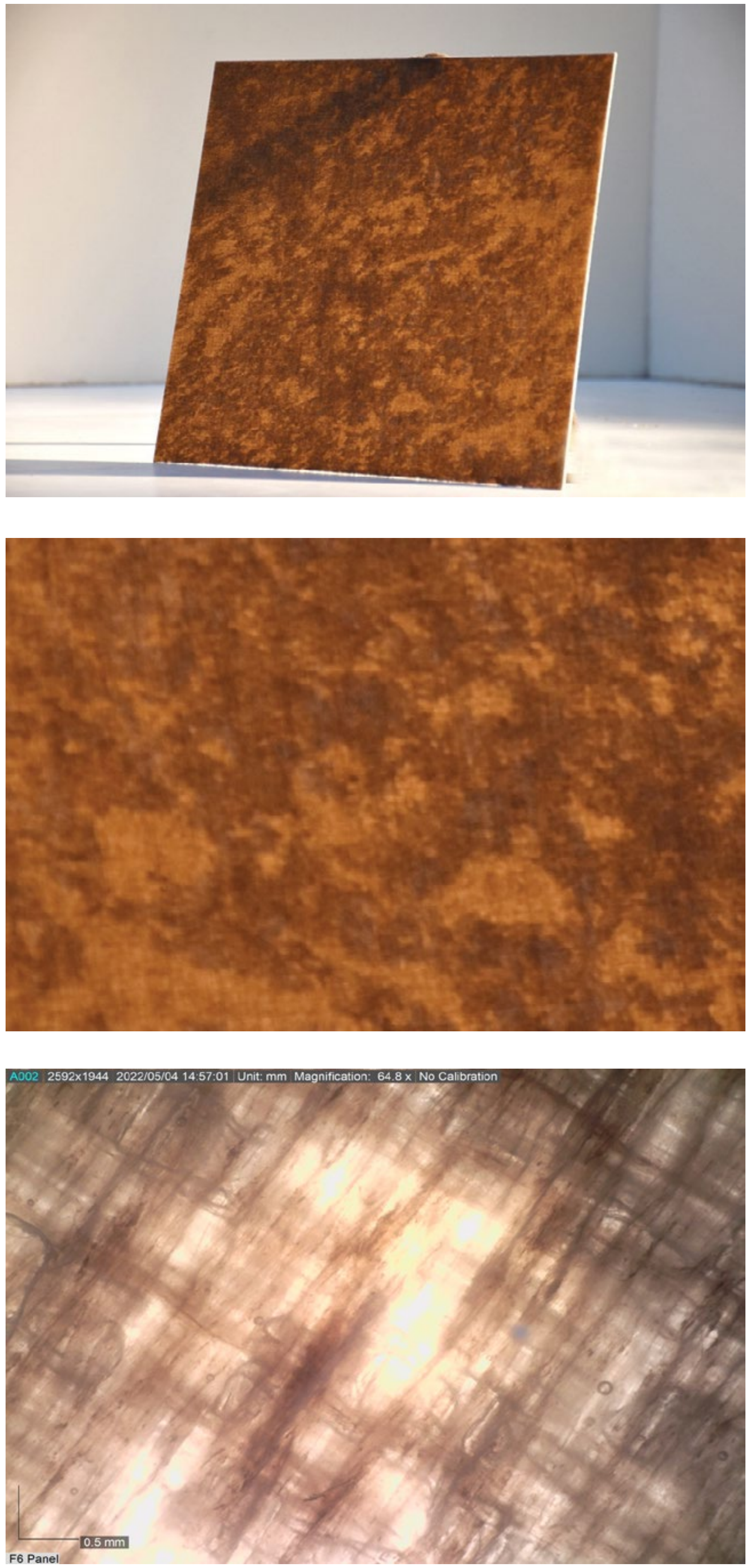


Figure 39: Panel F’6 (Top) - Texture of Panel F’6 (Mid) - Microscopic Picture (Bot)

Panel Name	Fiber Type	Size (mmxmm)	Number of Layers	Orientation (o)	Infusion Time (min)	Epoxy Used	Hardner Used	Epoxy : Hardner Ratio (g)
F"6	180g Cross Stitched Flax Fiber	300 x 300	6	(0, 90, 45, 45, 90, 0)	13	Sicomin Greepoxy	SD 7561	100:36:00

Table 38: Panel F"6 Fabrication Details

Panel	Thickness (mm)	Weight of Fibers (g)	Weight Matrix (g)	Density Fibers (g/cm^3)	Density Matrix (g/cm3)	Volume Fraction Fibers (-)			Volume Fraction Matrix (-)	Density Composite (g/cm^3)	Test Direction
						0°	*90°*	*45°*			
F"6	2	81	100	1.4	1.17	0.16	0.16	0.08	0.6	1.26	0

Table 39: Panel F"6 Composition details

Panel	Ultimate tensile Strength (MPa)	Standard Deviation of UTS (MPa)	Young's Modulus (MPa)	Standard Deviation of YM's (MPa)	Elongation (%)
F'6	104.55	7.72	2860.81	149.72	3.81
After Water Test	103.45	9.14	2765	95.5	3.765
After UV Test	96	11.56	2913	168	3.6
After Temp Test	108	12.5	3009	259	3.6

Table 40: Panel F"6 Mechanical Properties (before & after weathering conditons)

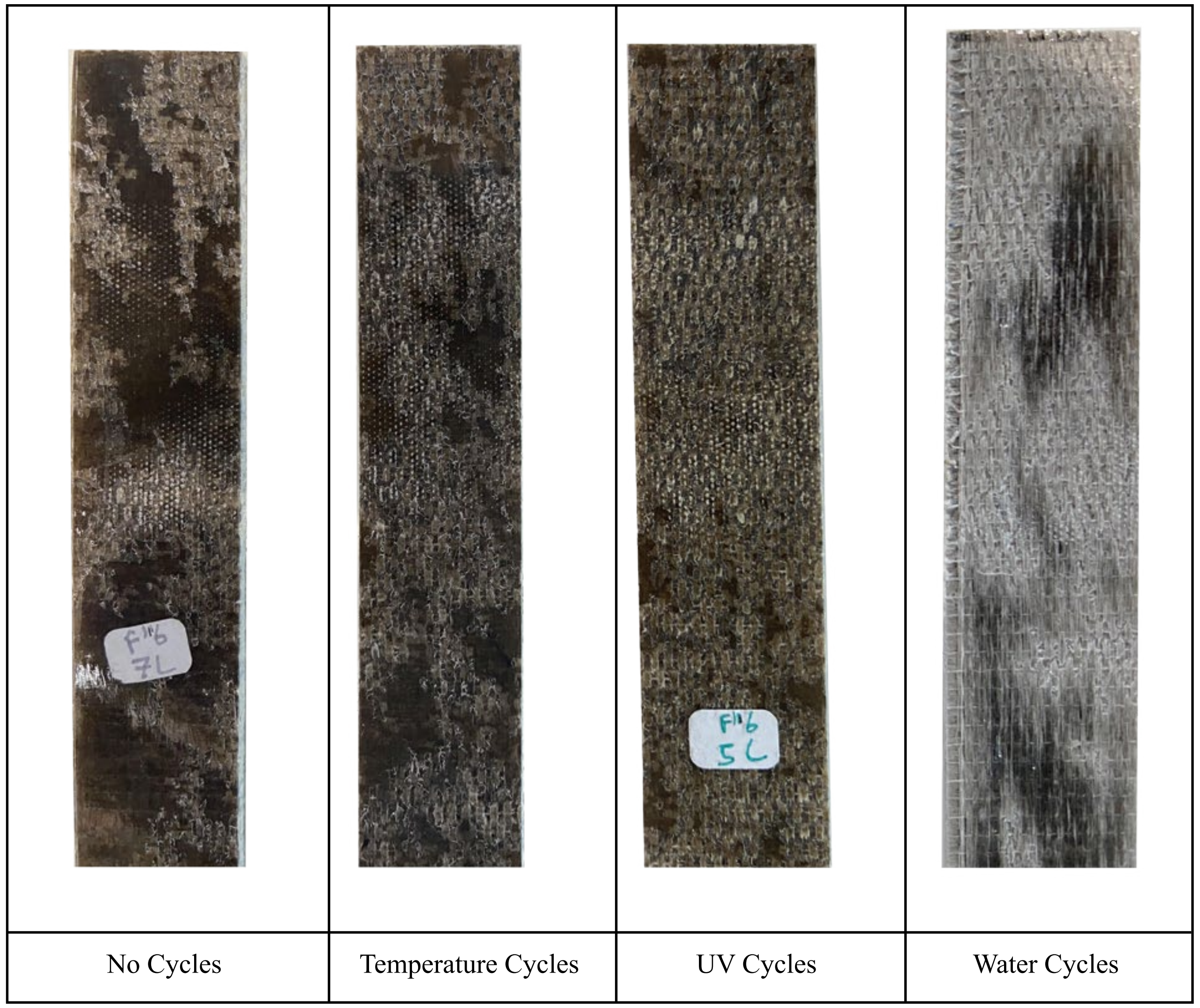


Figure 40: Panel F"6 before and after weathering conditions

Figure 41: Panel F"6 (Top) - Texture of Panel F"6 (Mid) - Microscopic Picture (Bot)

VI - Discussion of Results

01. Visual Interpretation

By observing the 4 panels, it is possible to visually compare 3 common aspects:

01.1. Reflectivity

From the experiment observations, the panel was found to copy the texture and finish of its mold. For example, a rough steel mat mold surface will lead to a mat rough finish in the panel. A glass mirror mold surface will lead to a glossy, reflective finish of the panel. The second factor is the releasing agent used on the surface. It is mandatory to use a releasing agent on any surface of mold to make sure that the panel could be removed after curing. Without the releasing agent, the epoxy will get completely stuck to the mold, the surface of the panel will have strongly visible defects, in some areas even, the fibers might be exposed which will lead to water-proofing problems. The releasing agent could be found as a wax or a spray and should be applied several rounds on the mold before the infusion process. There is a variety of products, and each one can affect the surface of the panel differently. The effect of the releasing agent on the panel is usually described on the product. Therefore, the client has the choice to control to a certain extent the finishing surface of the product. In the case of this research a releasing agent wax was bought from EasyComposites. The product is produced by Stoner (Molding Solutions). It is mentioned that the product enhances the reflectivity of the panel. The panels fabricated could be placed in the following ascending order of reflectivity ratio: F4<F2<F’6<F’’6

01.2. Translucency

The panels are all translucent, however in different levels. When being subjected to light from the back side, the material reflects it in the front side, in which the fiber organization become strongly visible, and light is emitted. Any movement on the back side of the material could be noticed on the front side. The translucency effect differs from panel to another depending on the type of fibers used and number of layers. F2 Panel which is made of Unidirectional Flax Tape (which consists of a series of Flax Fibers placed next to each other without any connection) shows the highest translucency effect among the 3 samples. In F4, the number of layers was doubled from 2 to 4, while using the same material (Unidirectional Flax Fiber Tape). In this sample (F4) the translucency effect is still available, however it is reduced. You can still see the effect of the light in the back transmitted and emitted in the front, however noticing movements becomes more difficult but it is still considerable. In F’6 & F’’6, the fibers used where different than the ones used in F2 and F4. In F’6 & F’’6, the fibers used were cross-stitched together, and the number of layers was increased from to 6 which affected the translucency of the panel. When the back-side of the panels F’6 & F’’6 are subjected to light, the light is still transmitted and emitted in the front side. The pattern formed in the panel due to the fiber organization illuminates. Any movement in the back-side could be strongly noticed in the front-side.

Visually, the panels could be placed in an ascending ratio of translucency, in the following order

F4< F’’6 & F’6<F2.

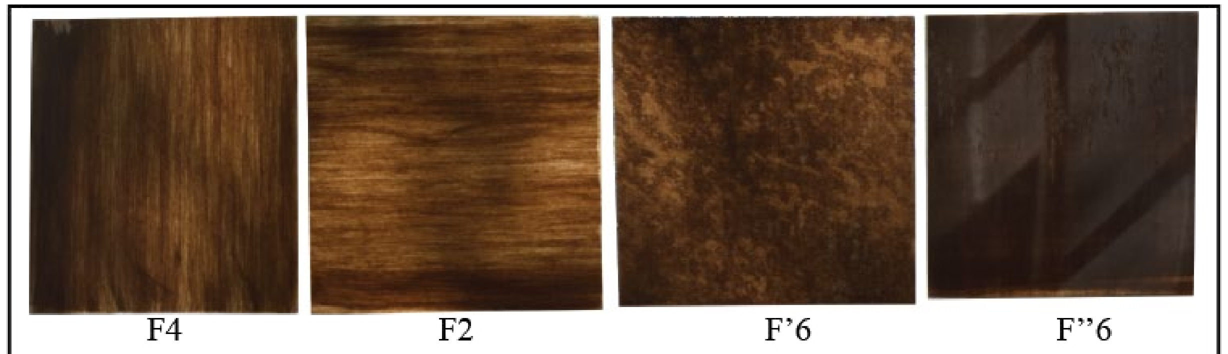


Figure 42: Panels front surface (Subjected to Sun light from front – Room light from back)

01.3. Flexibility

All the panels are considered flexible in different ratios. The panels could be bended using hand pressure. Once the pressure is released, the panel goes back to its initial state. This is directly affected by the number of layers, the density of the fibers, and its direction. In this experiment, it is observed that F4 requires less hand force to be curved, followed by F'6, F''6, and F4.

01.4. Effects of Accelerated weathering conditions on the appearance of the material

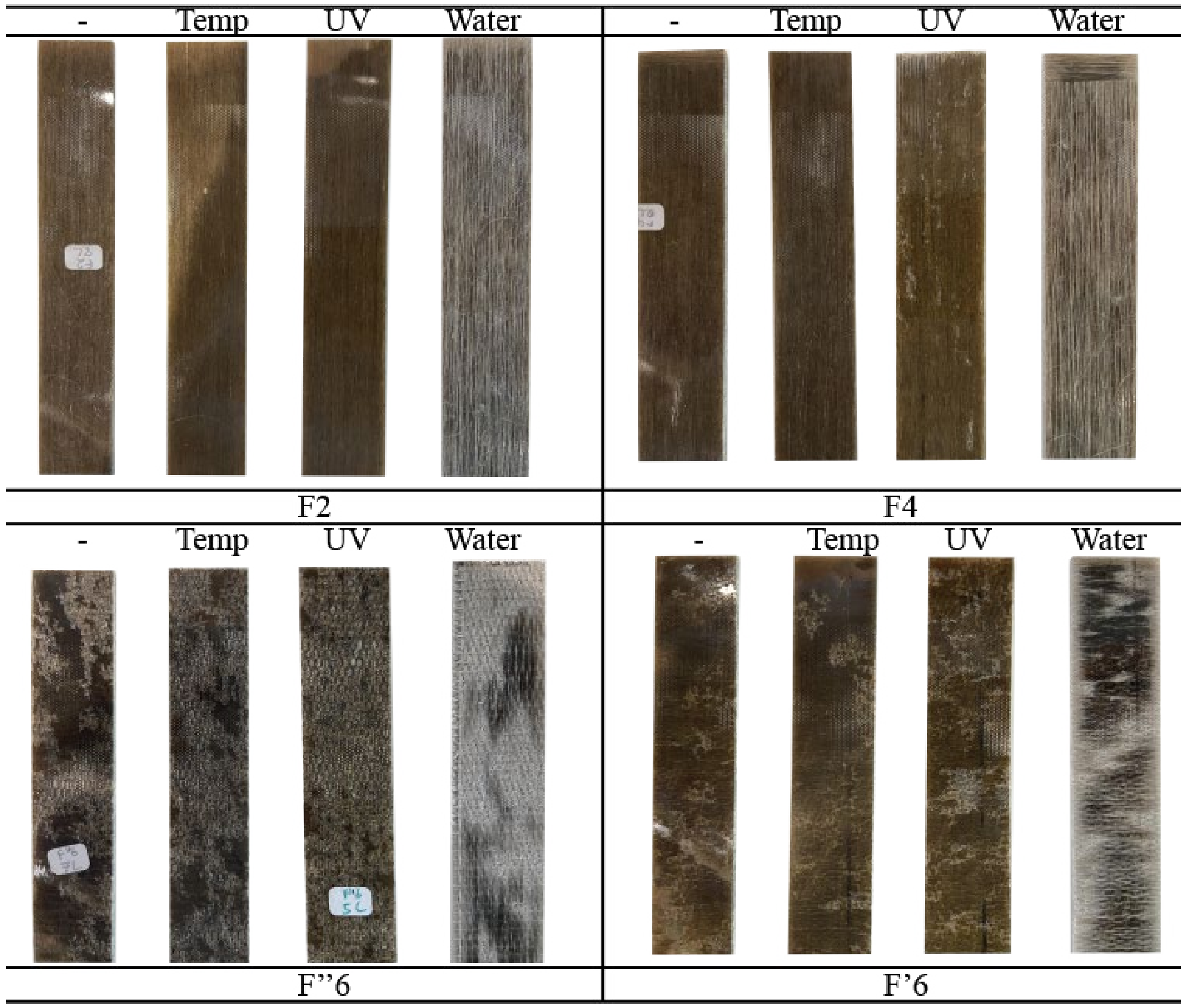


Figure 43: Before & After Weathering Conditions

Aspects like water, UV, and temperature can affect greatly the appearance of the material.

01.4.1. Temperature Effect on Material appearance:

By observing the samples after 4 days in the oven on high temperatures, it seems that there is no effect of high temperature on the material appearance. The feel of the surface, the color of the material, and the reflectivity remained the same.

01.4.2. UV light Effect on Material Appearance:

The UV testing machine affected the color of the samples, giving it a yellowish appearance that is clearly noticeable by observing figure 50. The samples were placed for a period of 5 weeks in a UV testing machine at TU Delft, which is equivalent to 5 years of exposure to direct sunlight.

01.4.3. Water Effect on Material Appearance:

Samples were completely immersed in salty water for a period of 7 days. The water had a very strong effect on the appearance of the material. The samples lost all their aesthetical characteristics. The surface became non reflective, the layer of epoxy on the surface disappeared, and the flax fibers became visible and touchable.

The material did not have any protective coating layer on it. By applying a protective coating layer, the material can withstand more the UV radiations, therefore the yellowish color will decrease. Other tested aspects (Water & Temperature) do not seem to have any visible effect on the appearance of the material.

01.5. Conclusion on Material Appearance before and after subjection to weathering conditions

Without any weathering conditions, Flax Reinforced Bio-Epoxy seems to have a very attractive appearance, similar to wood but with more reflectivity and translucency. However, by stimulating weathering conditions using UV testing machine (4 week), Oven (average 65º for 7 days), Water subjection (1 week immersion in salty water), it is observed that Flax Reinforced Bio-Epoxy, can be affected strongly by water leading to partial loss of its aesthetical characteristics, and the loss of the protective epoxy layer on the front, which means that water will be absorbed by the fibers leading to structural issues. Temperature does not seem to have any effect on the appearance of the material; however, UV light seems to give the material a visible yellowish surface that increase with time. With that being described, it is important to mention that the material did NOT have any protective coating on it surface. By applying coating surface, it is expected to decrease the effect of UV and Water on the material. The topic of coating could be a recommended topic for further researches, in which a mapping of bio-based coating could be elaborated, and tested for its efficiency.

02. Interpretation of Bending & Tensile Test Results

02.1. Mechanical Properties: Comparison with wood, Glass Fiber Composites, & Carbon Fiber Composites

To start with the interpretation of the data conducted from tensile and bending tests *(before weathering conditions)*, it is helpful to compare the calculated properties of the fabricated bio-composites, with other materials. Such as wood and petrol-based composites (glass fiber composites, & carbon fiber composites).

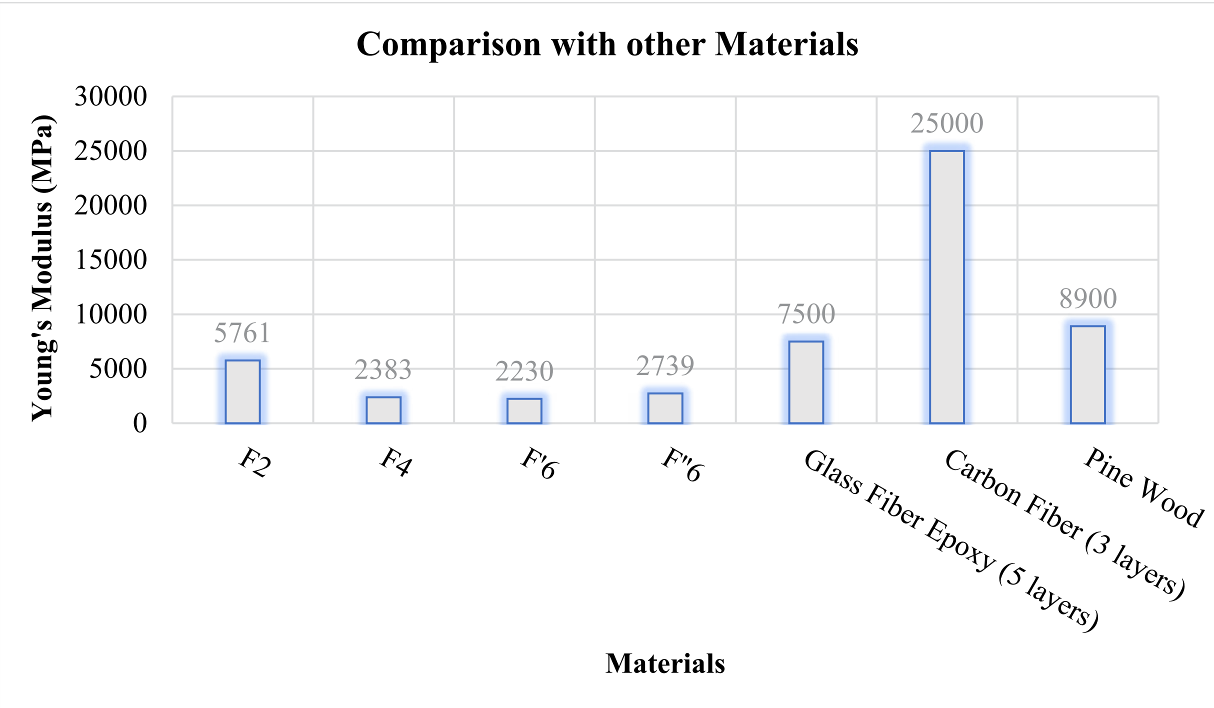
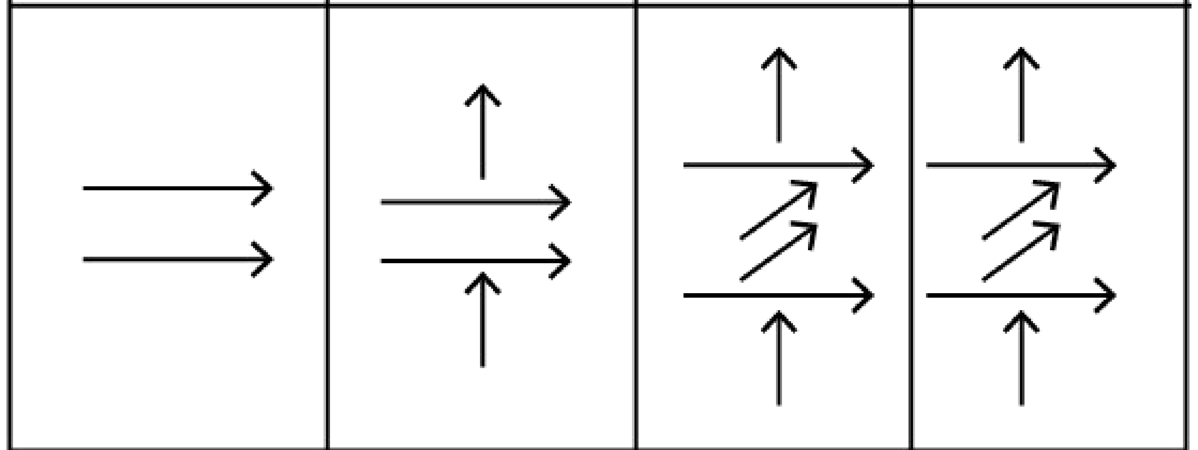


Figure 44. Comparative Chart of Fabricated Panels and other materials

In general, the stiffness of the bio-based composites fabricated is closer to glass-fiber composites and pine wood stiffness more than carbon fiber composites. Taking an average stiffness value of the 4 bio-based panels (3280 MPa) and comparing it to Glass Fiber Epoxy composite stiffness (7500 Mpa), it is clear that a glass fiber composite is stiffer that the bio-based version.

The number of layers used in the composites have a strong impact on its stiffness. For this reason, it is important to note that there is always the possibility to increase the stiffness by increasing the number of layers used.

02.2. Effects of Fiber Direction on Mechanical Properties of Specimens

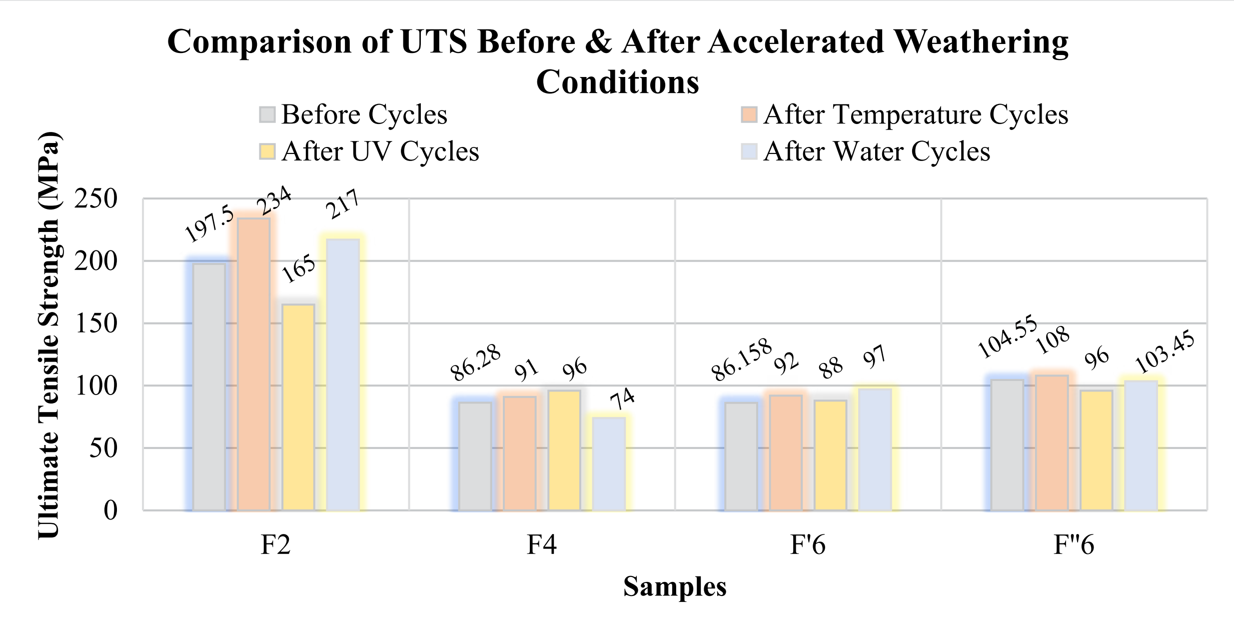


F2	F4	F'6	F"6
2 layers - 0,0	4 layers - 0,90, 90, 0	6 layers 0,90, 45, 45, 90, 0	6 layers 0,90, 45, 45, 90, 0
YM= 5761 MPa	YM= 2383 MPa	YM= 2230 MPa	YM= 2739 MPa

Figure 45. Relation between direction of fibers and stiffness

When the layers are placed in the same direction, the composite have the strongest stiffness if tested in the same direction of the fibers. Depending on the application, it is possible to have a thin panel stiffer than a very thick panel composed or opposed layers.

02.2. Effects of Weathering Conditions on Material’s Mechanical Properties



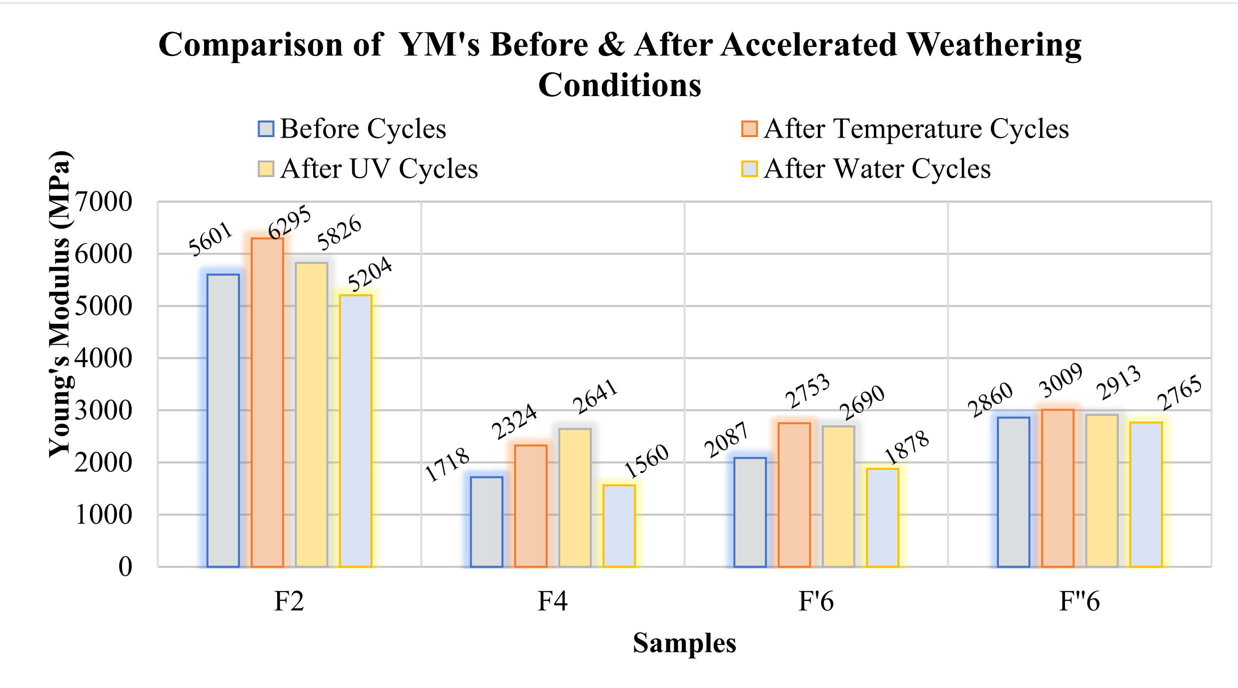


Figure 46. Comparison of UTS & YMs before and after weathering conditions

By comparing the stiffness of the material before and after subjection to water, UV, and high temperatures, it is possible to conclude that it does not have a huge impact on the stiffness of the material. However, it appears that the water is decreasing the stiffness of the material with a range of 100 – 400 MPa approximately. It also appears that UV and high temperature are

increasing the stiffness of the material, which means that the material is drying and curing more when subjected to “sunlight” leading to an increase in its stiffness.

In this research, and to be as safe as possible, the UTS and the Young’s Modulus with the minimal results will be used in the coming structural analysis and design proposal.

Panel	UTS (MPa)	STD UTS (MPa)	Young's Modulus (MPa)	STD YM (MPa)
F2	165	31.5	5204	432
F4	74	11	1560	118
F'6	87	2.72	1878	68
F''6	96	11.56	2765	95.5

Table 41. Used mechanical Properties from tests data

02.3. Relation between conducted data & design

The values conducted from the tests allows us calculate the serviceability limit state and the ultimate limit state to specify whether this material is acceptable as a construction material, and to understand what are the suitable applications for it.

Since the focus of research is on applying bio-composites on the building envelope, the initial design suggestion will be simplified to a simple rectangular panel (height: 3000 mm; width: 2000 mm). The panel is considered to be applied on the façade with 2 fixed supports attached on the floor slab and on the ceiling slab.

In this case, the panel will be subjected to wind loads. This wind load will be approximated to a distributed load applied on the panel. The maximum wind speed measured in the Netherlands during a storm is 60 Miles per Hour, which is classified as top-level storm and directly before the level 1 of hurricane. With an air density of 1.225 kg/m^2 this wind speed is equal to 9.216 PSF, which is equal to 0.44 kN/m^2 applied in a distributed way on the surface of the panel.

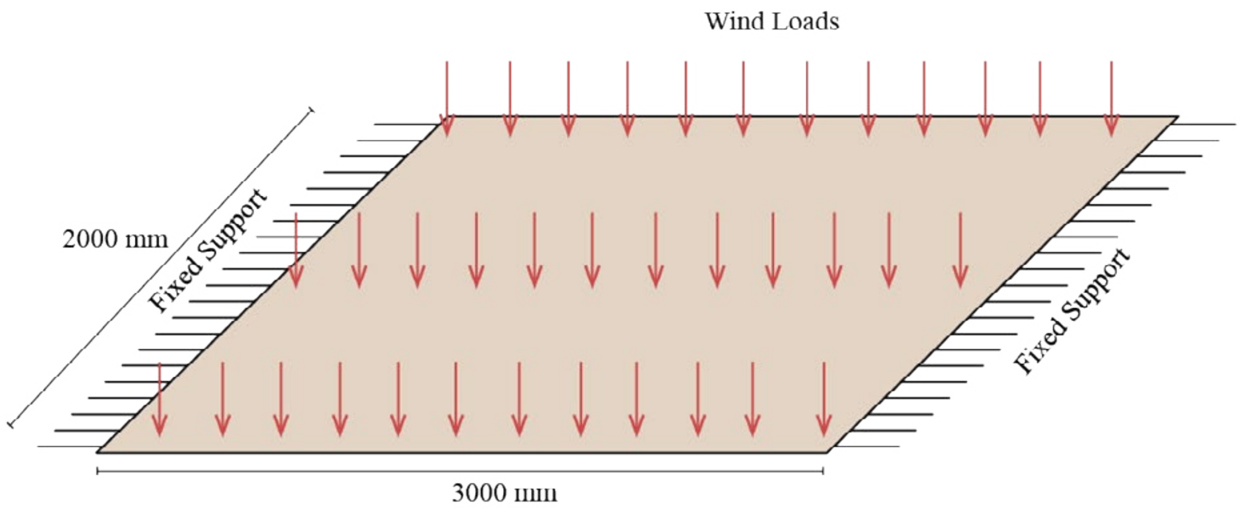


Figure 47. Simplification of wind loads on panel

02.3.1. Serviceability limit state: Deflection

As a first step of this analysis, checking the deflection of this material under wind loads is a necessity. For that the serviceability limit state for deflection will be set to the total span of the panel divided by 60. Which is similar to the allowable deflection of glass. With a span of 3000 mm, the allowable deflection is set to be 3000/100 = 30 mm.

<u>Case 1: Using the Panel F2</u>

Thickness (t) (mm)	1.2
Young's Modulus (E) (MPa)	5204
Moment of Inertia (I_x) (mm^4)	288
Span (l) (mm)	3000
Width (b) (mm)	2000
Cross Section Area (mm^2)	2400

Table 42. F2 Details

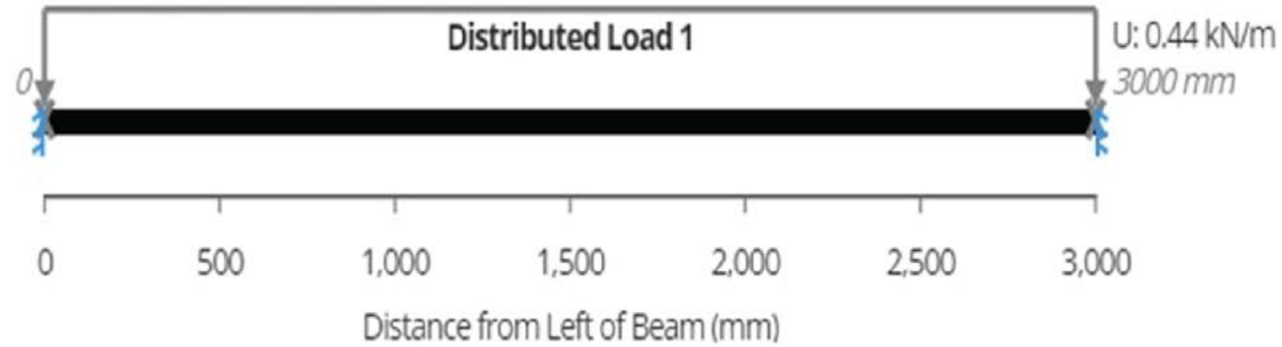


Figure 49. Case of Panel F2 wih loads

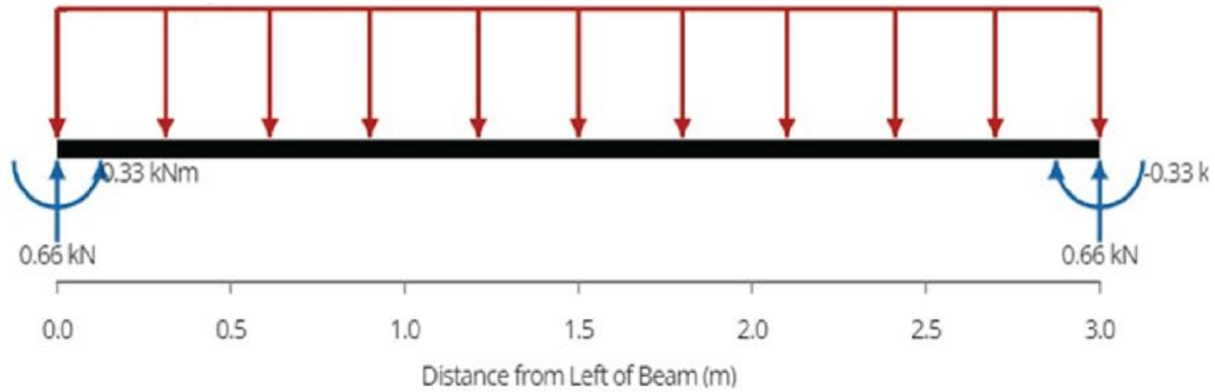


Figure 50. Load & Reaction Diagram F2

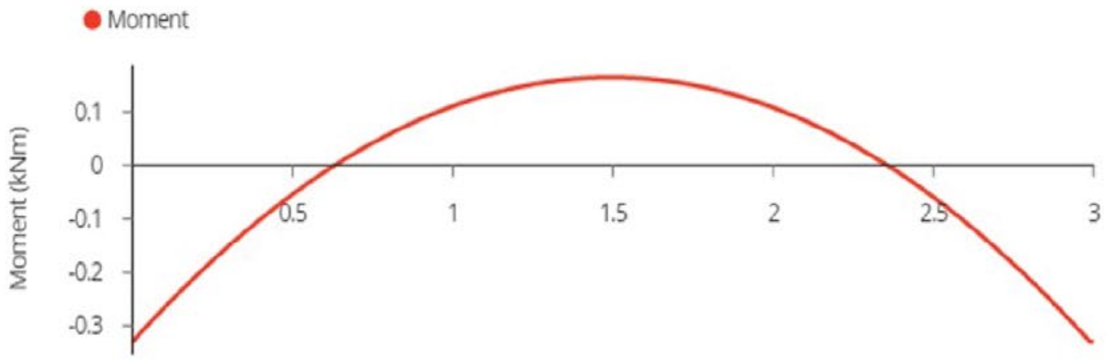


Figure 51. Moment Diagram F2

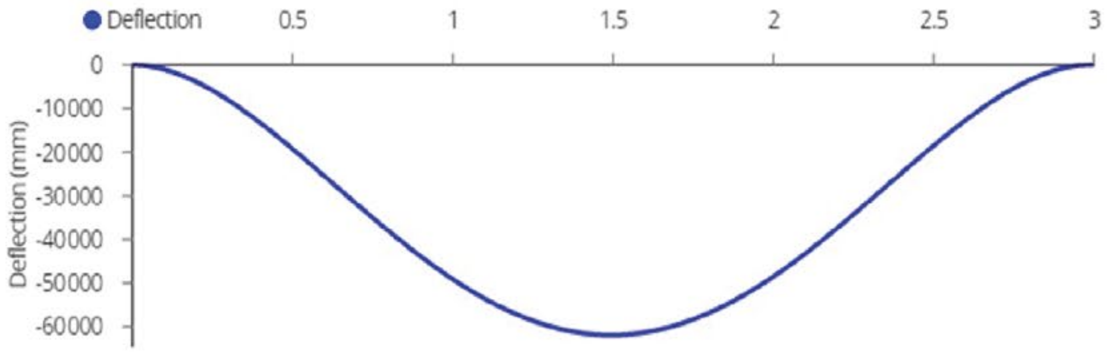


Figure 52. Deflection Diagram F2

The results of the calculations on panel F2 (thickness 1.2 mm – Flat sheet), when subjected to wind speed of 60 Mph shows that the material will deflect 61 900 mm, which means that the material will directly fail.

To decrease the deflection, 2 modifications could to be applied. They could be combined or applied separately.

Modification 1: Modify the geometry of the panel from flat to curved.

Modification 2: Increase the number of fiber layers.

In the case of this research, the first modification to be implemented is to modify the geometry of the panel from flat to curved. If the deformation is still higher than the allowable deflection, the panel thickness will be increased, and the structural check will be done again. The dimension of the curved panel will remain 3000 mm x 2000 mm. the highest point of the curve is 500 mm, as shown in the figure below

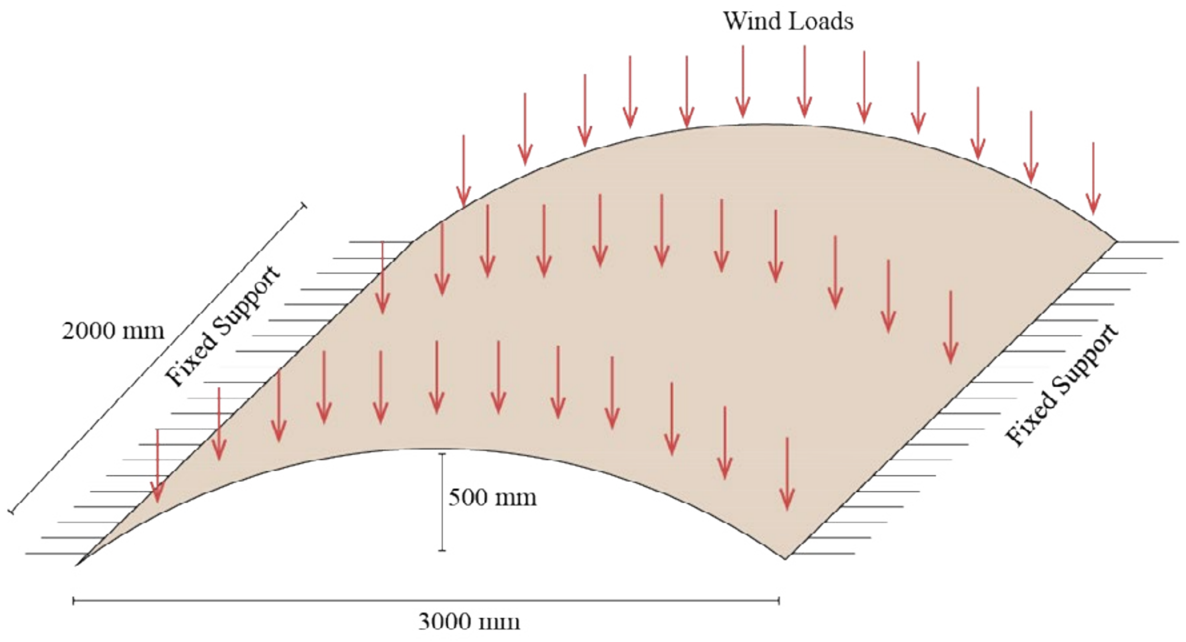


Figure 53. Panel Geometry modification

Curve Analysis using Karamba & Kangaroo:

In order to structurally analyze the curved shape, it was easier, and less time consuming to use a structural script on Grasshopper using the plug ins Karamba 3D and Kangaroo2. In brief, the script allows to (1) insert all necessary mechanical and physical properties of the material, (2) insert the supports and the loads, (3) insert the mesh or the shape of the element to be tested, (4) generate structural data (in the case of this study, deflection is the main aspects to be checked).

Analysis 1:

Panel Name	F2
Thickness of Material (mm)	1.2
Length (mm)	3000
Width (mm)	2000
Curve Height (mm)	500
Young's Modulus (MPa)	5204
Specific Weight (kN/cm^3)	14.7
Loads (Wind) (kN/m^2)	0.44
Support Types	Fixed

Table 43. Data input of Script

Results of Analysis:

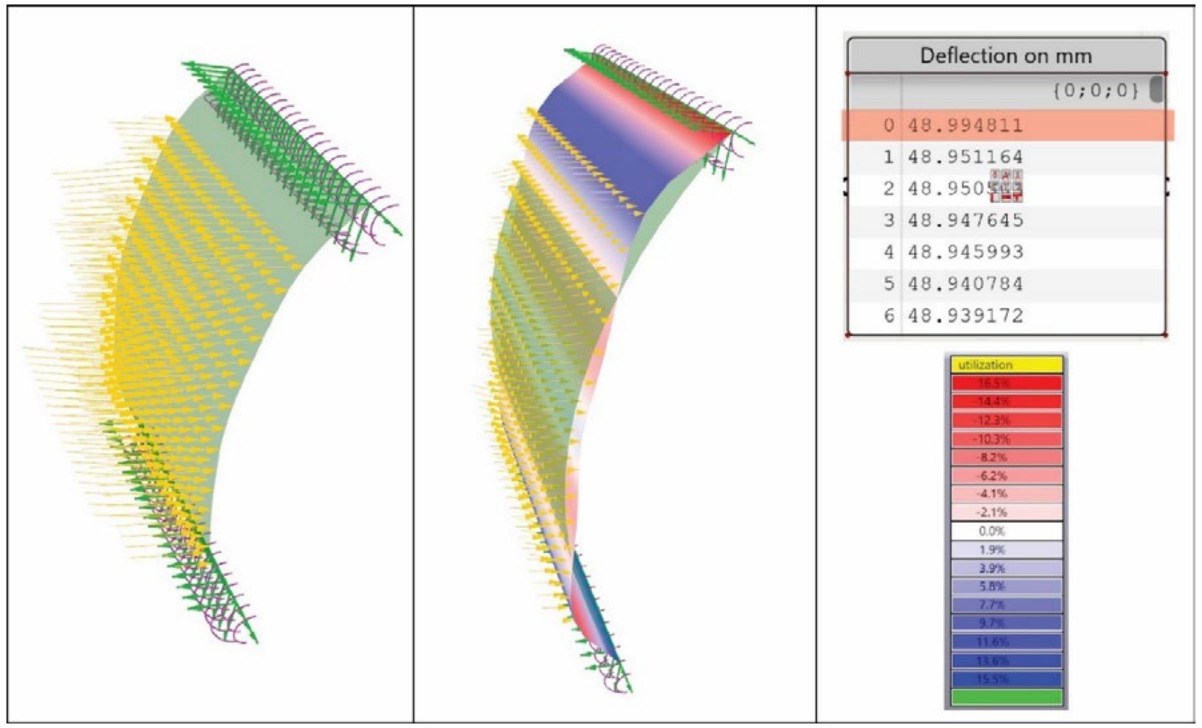


Figure 54. Script Analysis Visualization Results

The figure above shows the deflection of the panel under the conditions stated in table (-). The colors red, blue, and white refer to the utilization (%) of the material. **The maximum deflection conducted from the analysis is 48.994811 mm. The value is less than 50 mm. Therefore, it is considered accepted.**

Following the findings of this analysis, it appears by providing a curvature of approximately 500 mm radius on a span of 3000 mm leads to allowable deflection. However, another load is to be considered, which is the weight of the panel, and the weight of a wood frame and glass that will be placed in middle of the panel as shown in the figure below. The weight of the frame was considered 50 kg creating a load on the material on the Z direction.

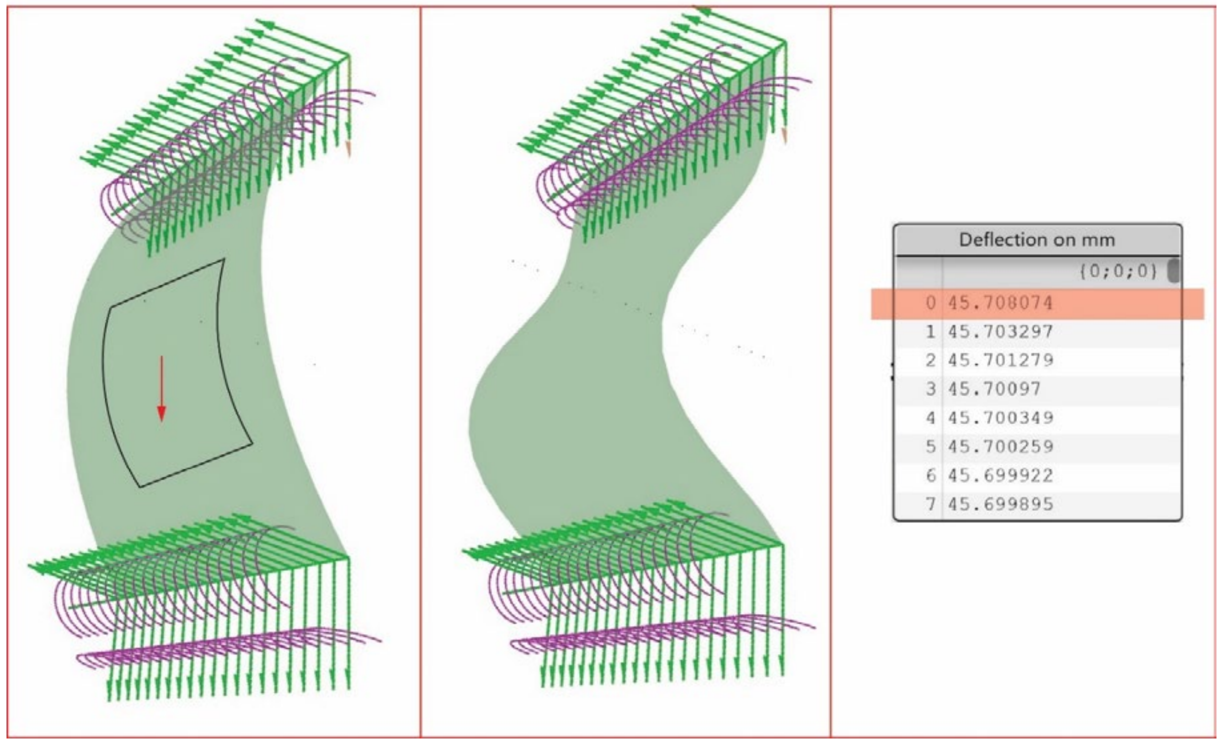


Figure 55. Script Analysis Visualization Results 2

With the input data, it appears that the panel will deflect 45.70 mm in the Z direction as seen in the figures above.

2 modifications could be done to reduce the deflection on the material due to weight.

Modification 1: Replace Panel F2 (1.2 mm thickness) with panel F4 (3 mm thickness)

Modification 2: Add stiffeners on the two sides on the material.

For this research the solution that will be analyzed is the increase of the number of layers from 2 layers to 4 layers of 200g flax unidirectional Tape. In that case, the panel that will be used is F4 instead of F2 and therefore the stiffness of panel F2 (5204 MPa) will be replaced by the stiffness of panel F4 (1564 MPa). The stiffness decreased due to the fact that panel F4 consists of 4 layers placed in the following order 0º, 90º, 90º, 0º. (refer to result section). The thickness of panel F4 is 3 mm. This example will be referred to as case 2: Panel F4

However, stiffeners will be added either way to the panel to make sure that the design will be stable and the deflection on the Z axis becomes negligible. *(Stiffeners will be shown in design part)*

Analysis of Case 2: Panel F4:

By inputting the new data shown below:

Panel Name	F4
Thickness of Material (mm)	3
Length (mm)	3000
Width (mm)	2000
Curve Height (mm)	500
Young's Modulus (MPa)	1564
Loads (Wind) (kN/m^2)	0.43
Weight Applied on Z direction (Kg)	50
Support Types	Fixed

Table 43. Data input of Script Panel F4

It is shown, that the deflection due to wind loads on the Y direction decreased to 10.46 mm. And the deflection due to the weight of the wooden frame and glass on the Z direction decreased to 24.36 mm.

Deflection on mm	{0;0;0}
0	24.36107
1	24.35908
2	24.358143
3	24.354083
4	24.342337
5	24.342194
6	24.341914
7	24.341668

Deflection on mm	{0;0;0}
0	10.460322
1	10.432075
2	10.428[illegible]
3	10.424[illegible]
4	10.406601
5	10.405463
6	10.403558
7	10.401725

Therefore the serviceability limit forstate was satisfied.

02.3.2. Ultimate Limit State

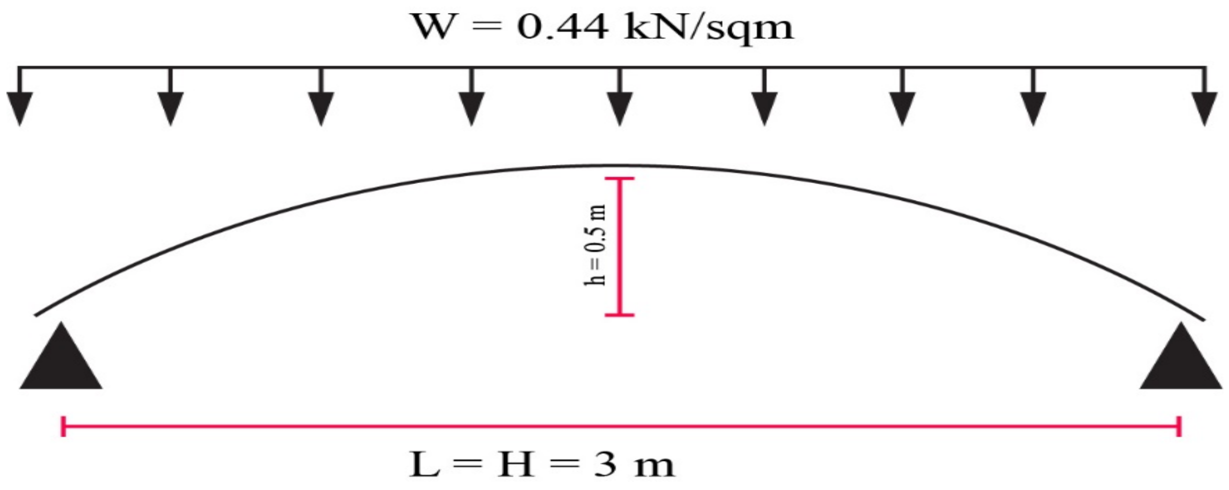
Another important factor to be checked is the ultimate limit state of the material. For that δ_{max} is to be calculated and checked if its lower than the ultimate limit state calculated using the following method:

$$Ultimate\ Limit\ State(MPa) = \frac{(Ultimate\ Tensile\ Strength - (1.64 * Standard\ Deviation\ of\ UTS))}{Pzrtial\ Safety\ Factor}$$

Since a partial safety factor for composites varies between 1.2 and 2.2 depending on the fiber used. Since the partial safety factor for flax is still not available, the highest value was used for this study which is **2.2**.

Panel F4 will be taken into consideration for this calculation, since it was proven to have deflection values lower than the allowable deflection.

Panel F4:



*Ultimate Limit State = (74 – (1.64 * 11)) / 2.2 = 25.44 MPa*

$\delta max = M_{max} / Z$

with $Z = \frac{\text{width} \times thickness^2}{6}$

$\delta max = 1.1 * 10^{-4}$ *MPa*

$\delta max <$ *Ultimate Limit State.* Therefore, the ultimate limit state was satisfied in for the proposed design using the panel F4.

Case 3: Panel F'6 & F''6

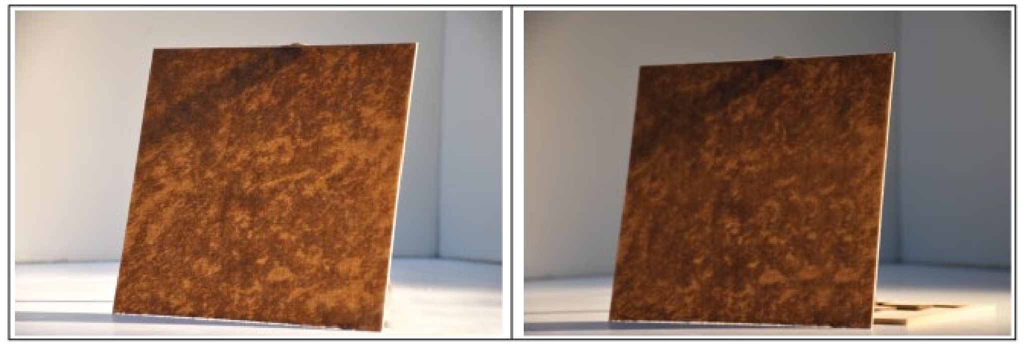


Figure 56. Panel F'6 and F''6

As an additional analysis to this research is to check if the other panels (F'6 and F''6) can also satisfy the ultimate limit state and the serviceability limit state. F'6 and F''6 have the same composition of fibers and epoxy, however F''6 was repeated due to a manufacturing issue. The panel was removed from the mold before the total curing of epoxy; therefore, the outer surface is defected. The panels did not show the same results in terms of stiffness and ultimate tensile strength, and this caused by the fact that the tensile tests were done in different ways. For panel F'6, the tensile test was done in the direction opposite to the majority of fibers. For panel F''6, the tensile test was done in the direction of the majority of fibers.

The analysis was done using the same dimensions of panel, and same loads used in the 2 previous cases (F2 & F4). The data will be presented in the following table:

Panel		Thickness (mm)	Ultimate Tensile Strengh (MPa)	Standard Deviation (Mpa)	Young's Modulus (Mpa)	Loads	Serviceability Limit State			Ultimate Limit State		
							Allowable Deflection (mm)	Deflection Y (mm)	Satisfied	ULS (Mpa)	δ_{max} (Mpa)	Satisfied
F'6		2.5	88	4.56	1878	Wind + Weight	30	15.04	YES	36.6	9.6	YES
F''6		2	96	11.56	2765	Wind + Weight	30	19.9	YES	35.01	1.5	YES

Table 44. SLS and UTS for panels F'6 and F''6

02.4. Conclusion on Structural Analysis of Panels F2, F4, F'6, and F"6

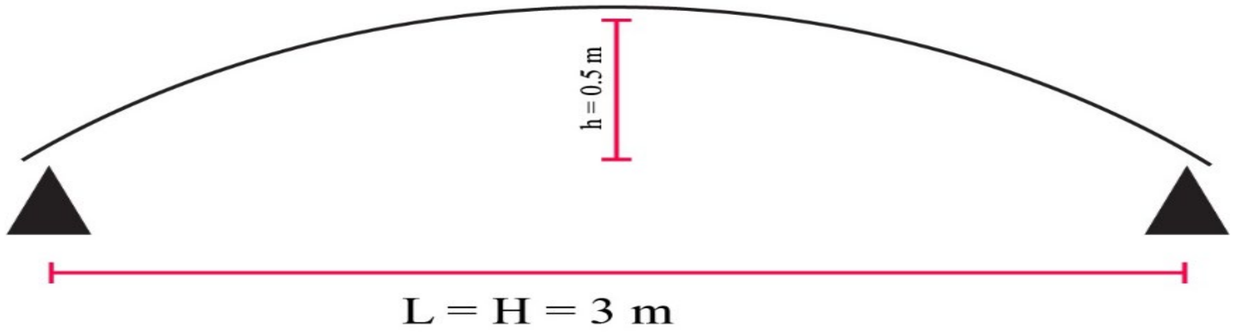
With the available data calculated from the tensile and bending test results, and by taking into account the decrease in the material stiffness and ultimate tensile strength after subjection to weathering conditions, it could be concluded that on a size of 2000 mm by 3000 mm, Flax-Reinforced Bio-Epoxy could not be applied without including a curve to the geometry. Using the grasshopper script with Karamba and Kangaroo (Appendices -), the relation between the curvature radius and deflection due to wind loads and self-weight of the material was analyzed. It could be concluded that with a 500 mm height arch spanning 3000 millimeters, the serviceability limit state and the ultimate limit state will be satisfied as shown in the table below.

Panel	Thickness (mm)	Ultimate Tensile Strength (MPa)	Standard Deviation (Mpa)	Young's Modulus (Mpa)	Loads	Serviceability Limit State			Ultimate Limit State		
						Allowable Deflection (mm)	Deflection Y (mm)	Satisfied	ULS (Mpa)	δ_{max} (Mpa)	Satisfied
F2	1.2	165	31.5	5204	Wind + Weight	30	48.9	**NO**	51.52	2.5	**YES**
F4	3	74	11	1564	Wind + Weight	30	10.46	**YES**	25.44	1.1	**YES**
F'6	2.5	88	4.56	1878	Wind + Weight	30	15.04	**YES**	36.6	9.6	**YES**
F''6	2	96	11.56	2765	Wind + Weight	30	19.9	**YES**	35.01	1.5	**YES**

Table 44. SLS and UTS for panels F'6 and F''6

According to the analysis, panel F4 consisting of 4 layers of 220g unidirectional flax tape in the order (0º, 90º, 90º, 0º) is shown to have the best values for satisfying the serviceability limit state, the ultimate limit state, followed by panel F'6 and F''6 consisting of 6 layers of 180g cross-stitched flax fabric in the order (0º, 90º, 45º, 45º, 90º, 0º). And finally, panel F2, which is the thinnest panel (1.2 mm) consisting of 2 layers of 220g unidirectional flax tape in the order (0º, 0º).

For the panels F4, F'6, and F''6, the maximum deflection noted due to wind is 19.9 mm, when the panel is curved with maximum curve height of 500 mm as shown in the figure below.



This means that the curvature of the panel could be reduced for less than 500 mm, allowing the geometry of the panel to be modified, and therefore more options in terms of design. The weight of the material itself and the addition of a wooden window frame on the panel led to deflection on the Z axis equal to 29 mm maximum (Panel F2). To provide more stability on the Z axis, stiffeners will be added during the design. The stiffeners used could be either wood, or flax reinforced composites. This will be tackled in the design chapter.

VII - Façade Application & Design:

With the interpretated data and the structural checks, it is now possible to provide a possible design that could be applied on the building envelope.

Knowing that this research provides only an initial understanding of the reaction of the material in front of weathering conditions, and since there is much deeper analysis that must be conducted to fully prove the performance of this material, it is preferable to choose an application that could be combined with other materials to make sure that the climatical and safety requirements as satisfied. For that, it was decided to use this material as a second skin on double skin facades.

01. Definition of Double Skin Façade:

Double Skin Façade is a multilayer structure composed of an outer skin (usually glass), and an inner skin (usually glass). It is mainly used to provide a better climatic condition, and to reduce the energy consumption from active ventilation. There are 3 main systems of double skin facades:

01.1 Buffer System

Dating back to 100 years and are still in use. They use 2 layers of single glazing spaced 250 to 900 mm apart, allowing fresh air to circulate through the cavity. Devices for shading could be implemented in the cavity if needed.

01.2 Extract-Air System

It is composed of a double-glazing interior, followed by an air cavity and an outer single glazing layer. The air in the cavity is extracted by the HVAC system. The space between layers of glass ranges from 150mm to 900mm. This system is highly used in locations where natural ventilation is not possible due to high noise, or fumes.

01.3. Hybrid system

This system consistes combines various aspects of the above systems and is used to classify double skins systems that do not fit in the above mentioned types. Such systems may use non-glazed or non-conventional outer layer that act as a environmental barrier.

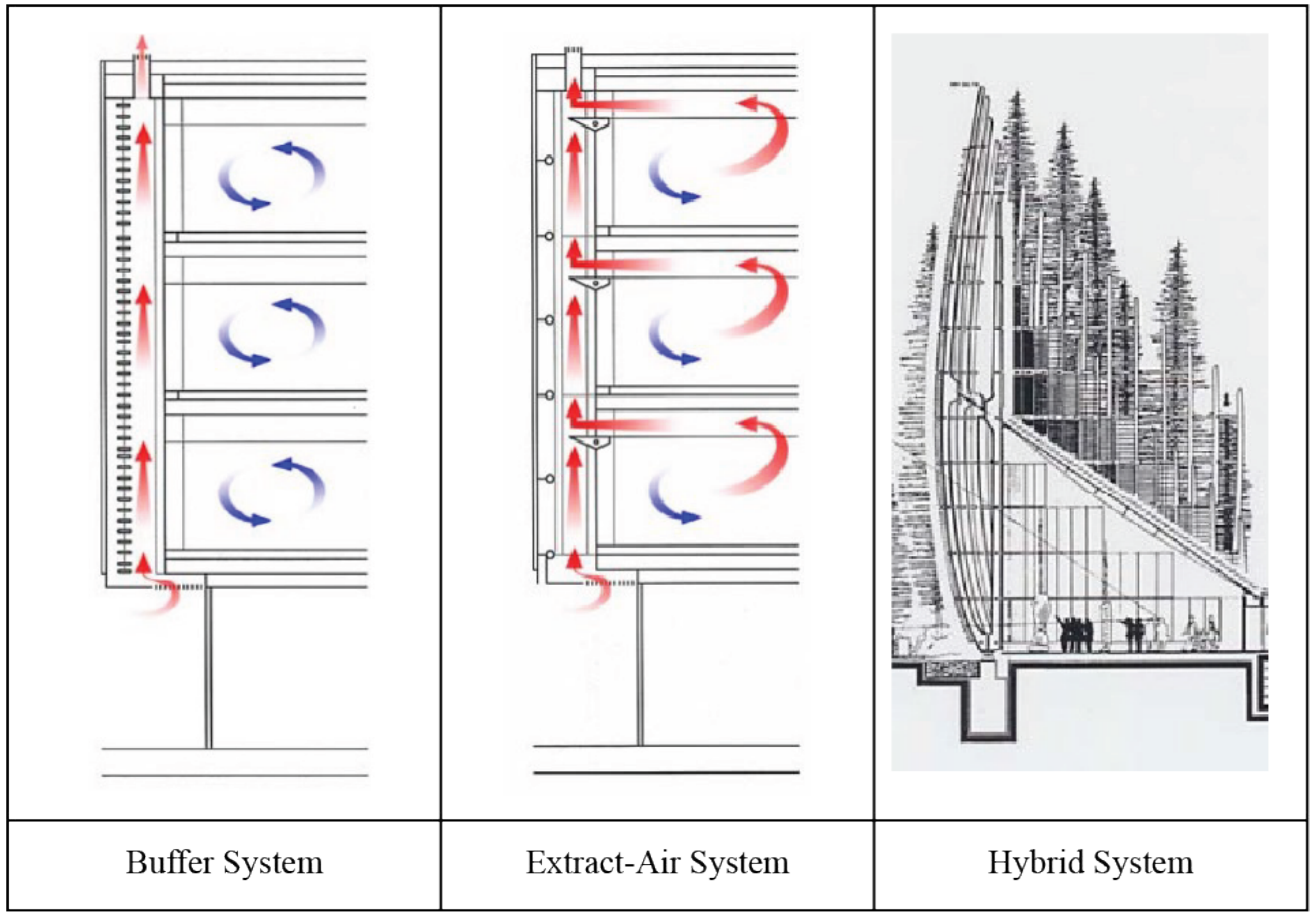


Figure 57. Double Skin Options

02. Façade System Design

For this research, the system that will be used is a Hybrid Prefabricated Unitized System. It will consiste of a inner double glazing layer, followed by a layer of non-wood bio-based composite fabricated through out this research. The system is prefabricated as unit (floor to ceiling) and connected to the slabs thorough brackets. The type of ventillation in the cavity of this system is natural, and the cavity is only accessible for cleaning through the interior skin.

02.1. Purpose of the system

Generally, most double skin systems are made out of glass, which make the designer limited in the design of the building envelope. Freeform facades will be challenging is the material used on the outer skin could not be shaped. Therefore, the first goal of the proposed design, is to show the potential of non-wood bio-based composites in generating forms that could not be reached with conventional materials. It is always possible to argue that the same design could be achieved using other type of fibers such as glass, kevlar, or carbon, however, when comparing the embodied energy of this material with bio-based option, it becomes clear why a bio-based option is worth exploring.

With the increase in environmental challenges, the increase in prices of petro-bsaed materials and their negative impact on environment. It is crucial to suggest bio-based solutions. For that, the second goal of the design is to provide a bio-product with a low negative environmental impact, and a low embodied energy.

From a technical point of view, the goal of this façade is to act as an environmental barrier between the interior and the exterior milieu. What is meant by environmental barrier, is a system that can reduce the noises commimng from outside, ventilate the interior skin therefore reducing the need for active heating or cooling, and finally provide a variety of aesthetical options showing the potential of this material.

Double Skin Type	Air Cavity	Ventilation in Cavity	Category	Type of Inner Openning	Shading device in cavity	Purpose of facade
Hybrid Prefabricated Unitized System	Not Accessible Non-continuous Maximum 500 mm	Passive Every unit is ventilated separetely	Air tight interior skin Non-airtight exterior skin	Bottom hung tipped casement OR Side hung casement	Not avaialable	Noise Reduction Inner Skin ventillation Freeform design

Table 45. Double Skin Façade Details

02.2. Slab and Brackets

In the above figure, details about the connection of the bracket to the slab are provided. The sytem could be applied to new buildings as well as old buildings (if all façade systems were dissambled).

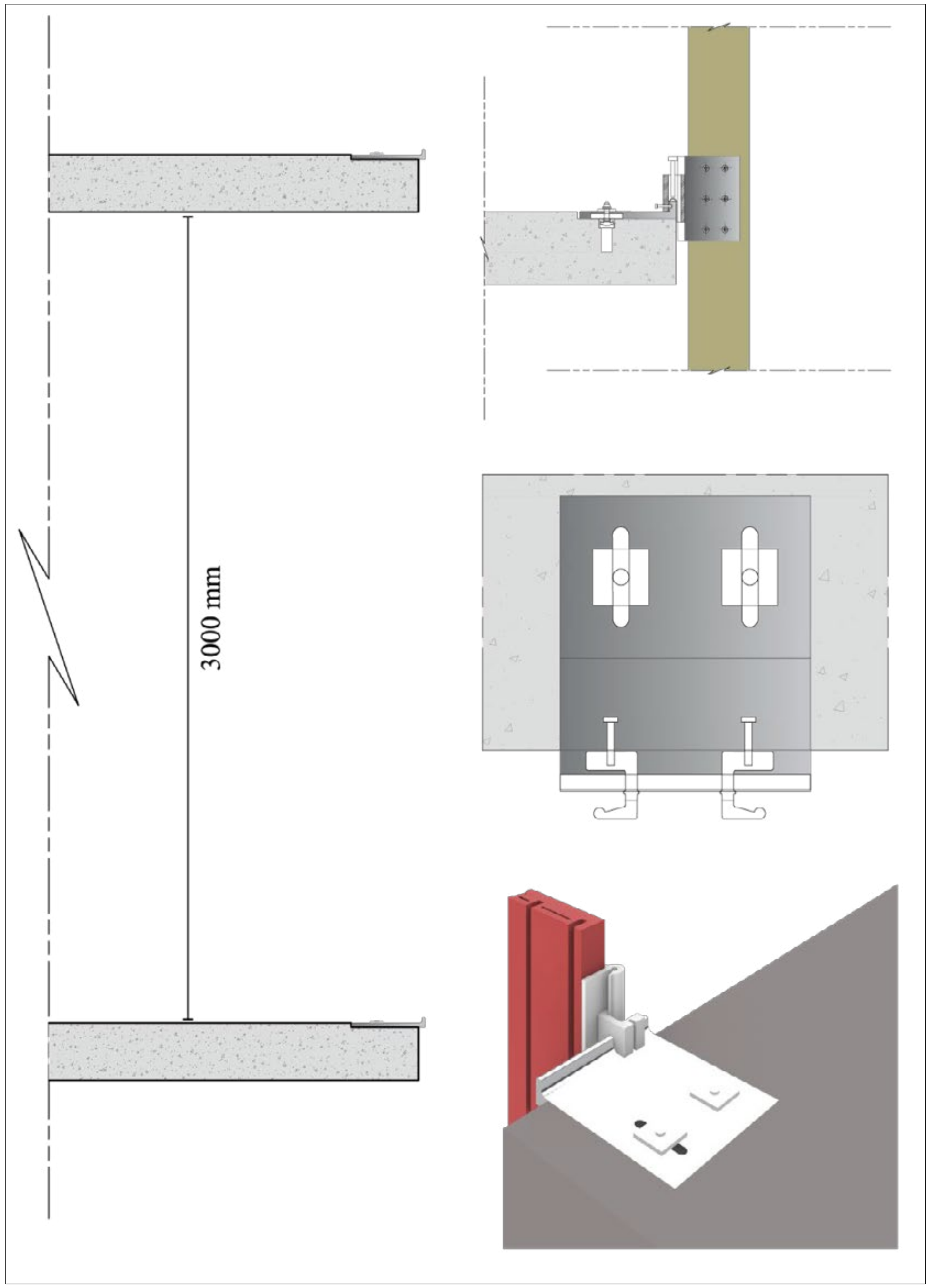


Figure 58. Bracket & Slab Details

02.3. Prefabricated Unitized System

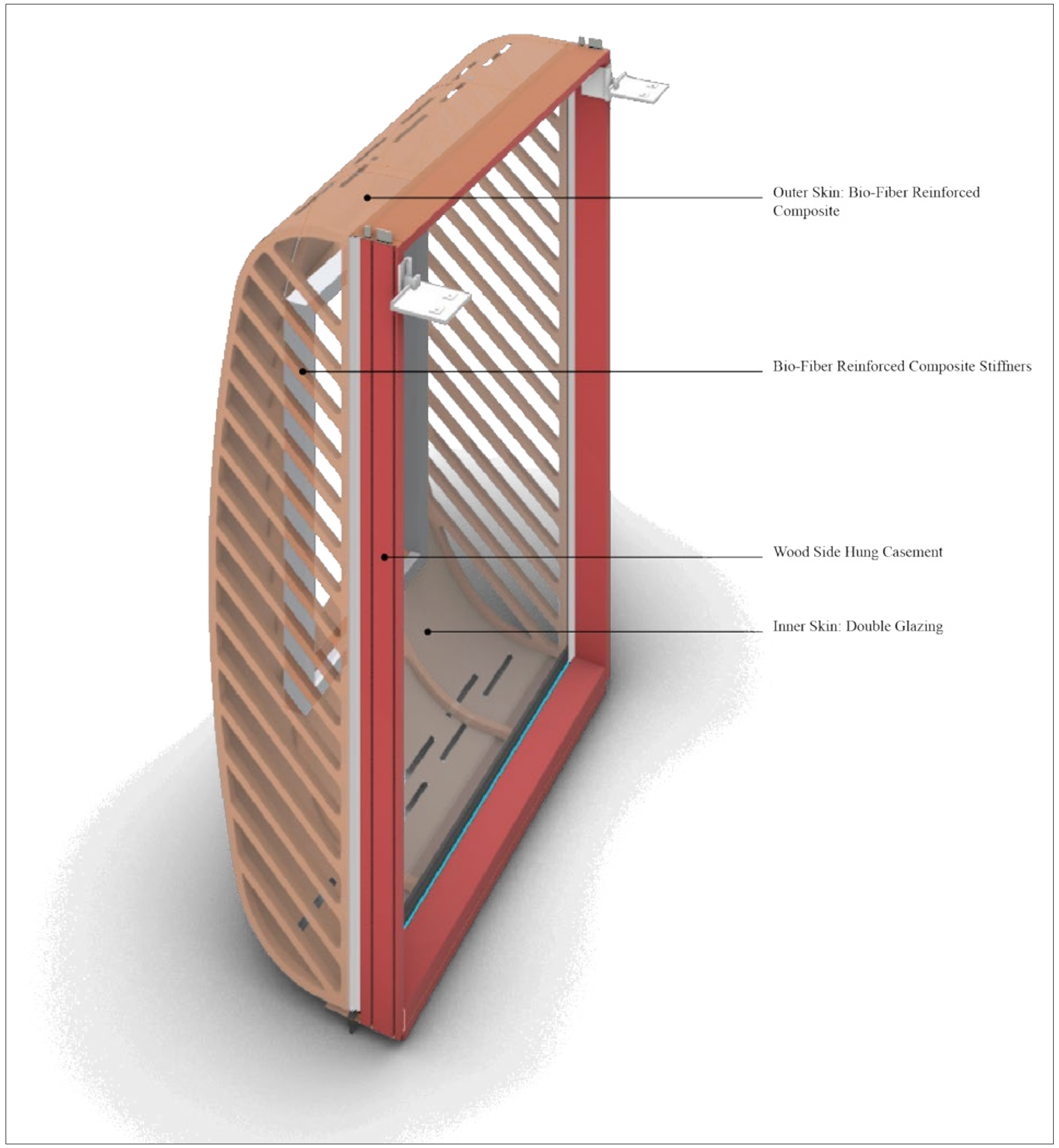
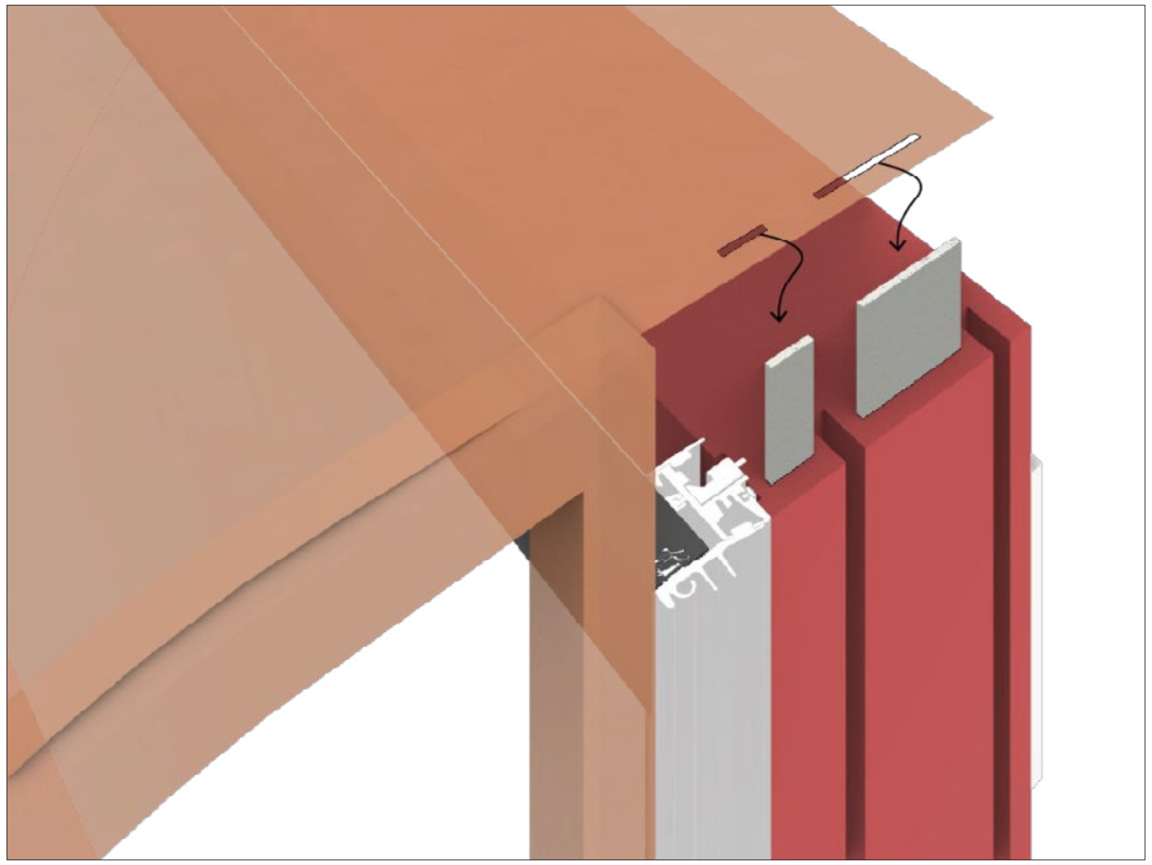


Figure 59. Unitized System Overview

The unitized system consistes of a wood side hung casement system with double glazing and followed by the outer skin that is fabricated using the VARTM Process and using Flax Fiber & Sicomin Bio-Epoxy. It is possible to modify the shape of the outer-skin to any geometric shape preferred as long as it fits the dimension of the wood window frame, and as long as the top and the bottom edges could be fixed to the window frame.



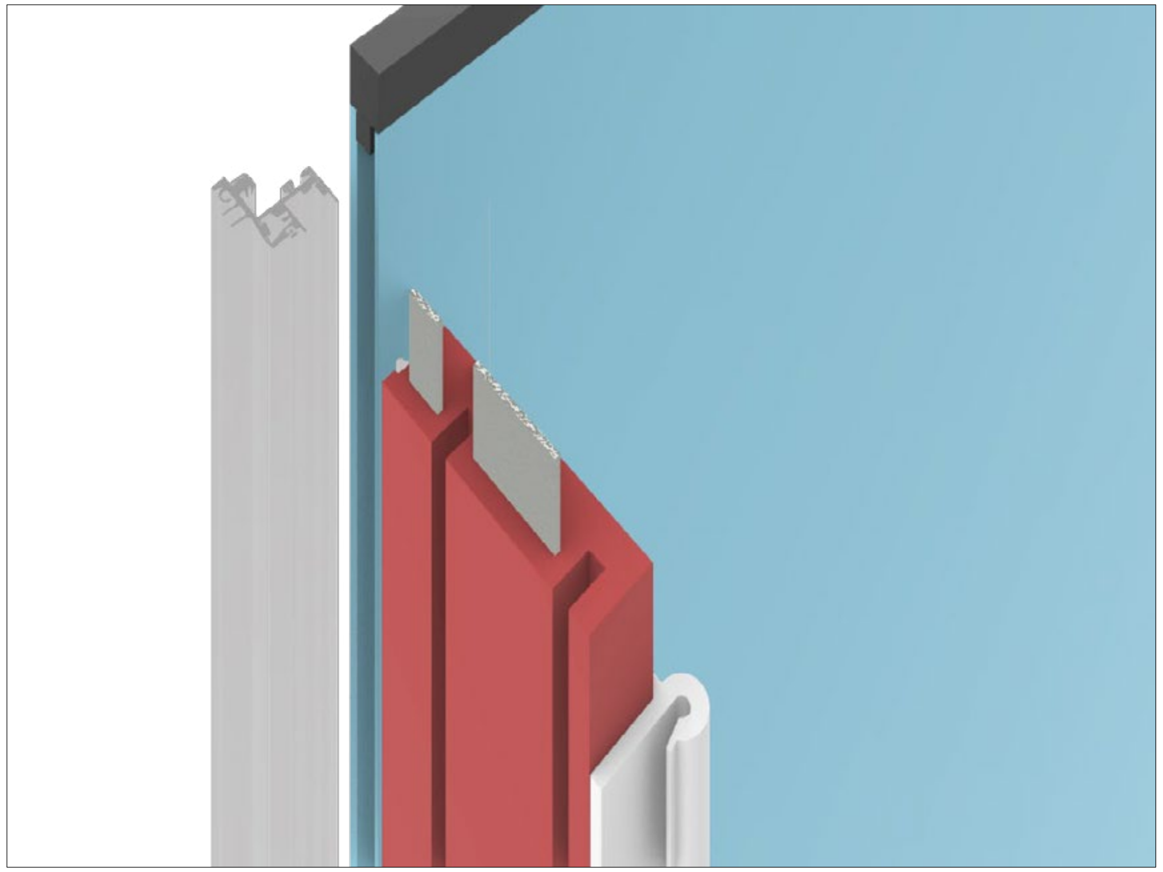


Figure 60. Unitized System Details

02.4. Bio-Based Panel

In this option, the shape of the bio-based panel is similar to the shape that was tested and approved in the analytical section. In which the panel has a curved span with a maximum radius arch of 500 mm. The shape of the panel is used to show the potential of the material to be curved in several directions in the same time. It originally generated from the following designs:

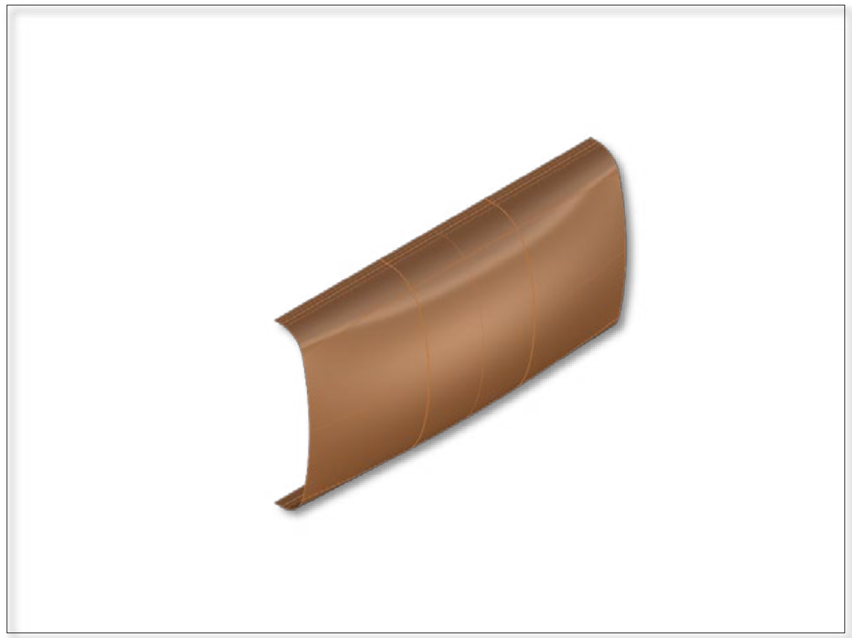


Figure 61. Shape Generation

This shape was furtherly developed to include openings for visibility and for connections.

Figure 62. Shape Generation 2

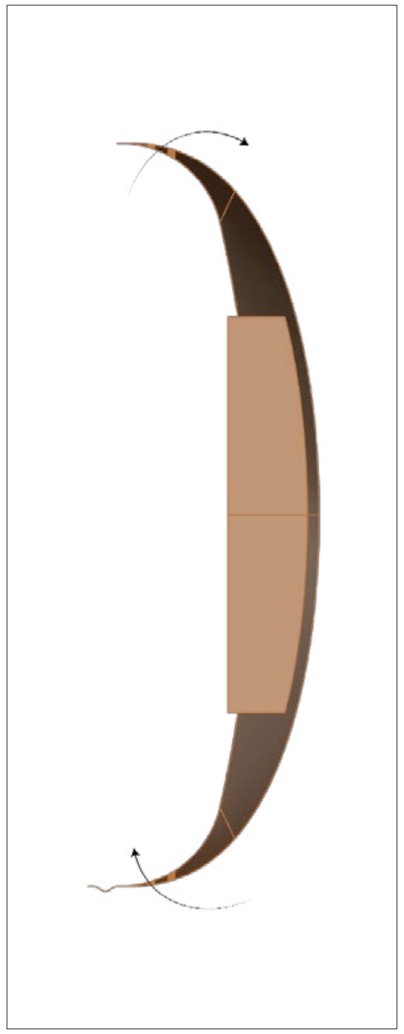


Figure 63. Ventilation of Panel

Horizontal openings were added on the bottom and the top of the panel to allow ventillation. However this will allow the water to come in. For that a gutter is needed to channel the water outside. This can be achieved by shaping the panel and adding a gutter on the bottom part.

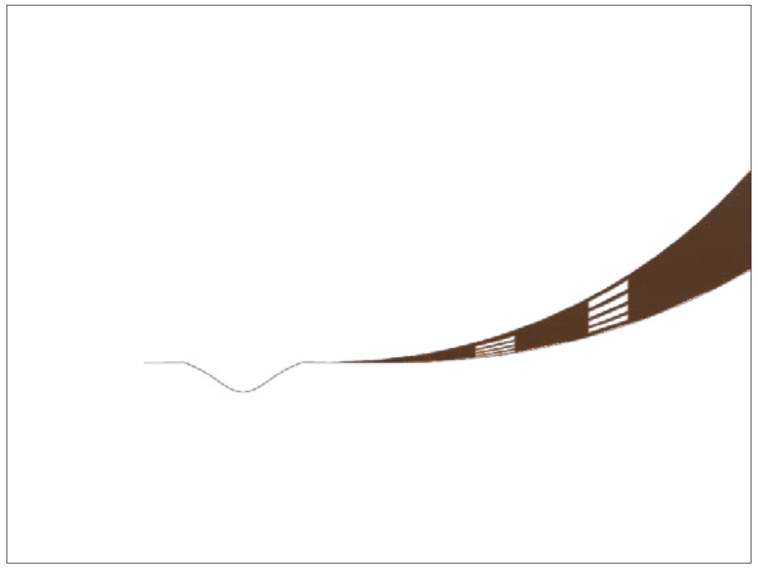


Figure 64. Gutter in Panel

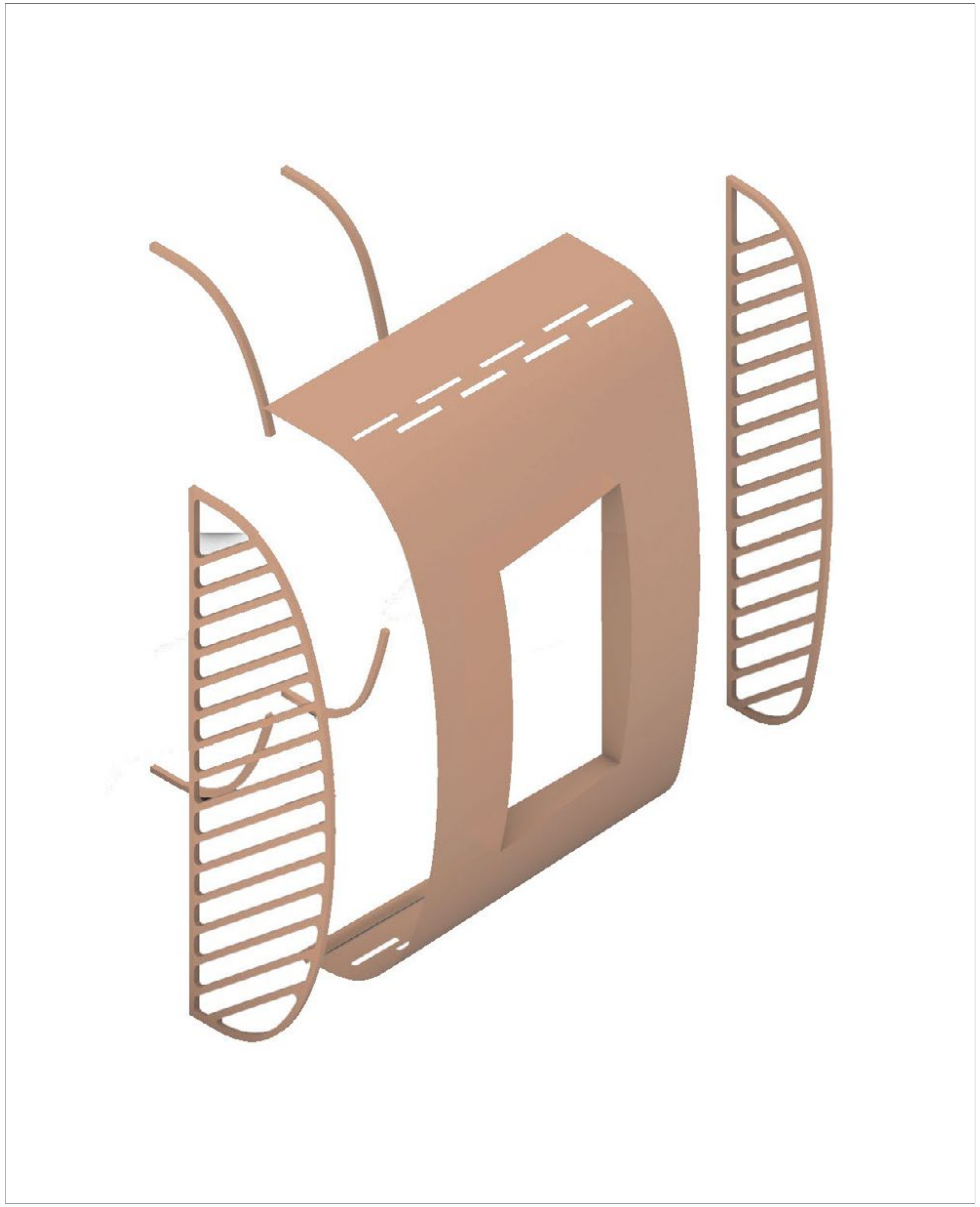


Figure 65. Stiffeners

02.6. General Shape

To show the capability of this material to curve in both directions X & Y, it was decided on this specific design. The last goal of this research is to provide a façade system and for this reason, the following chapter will show all the details needed to understand the system is constructed.

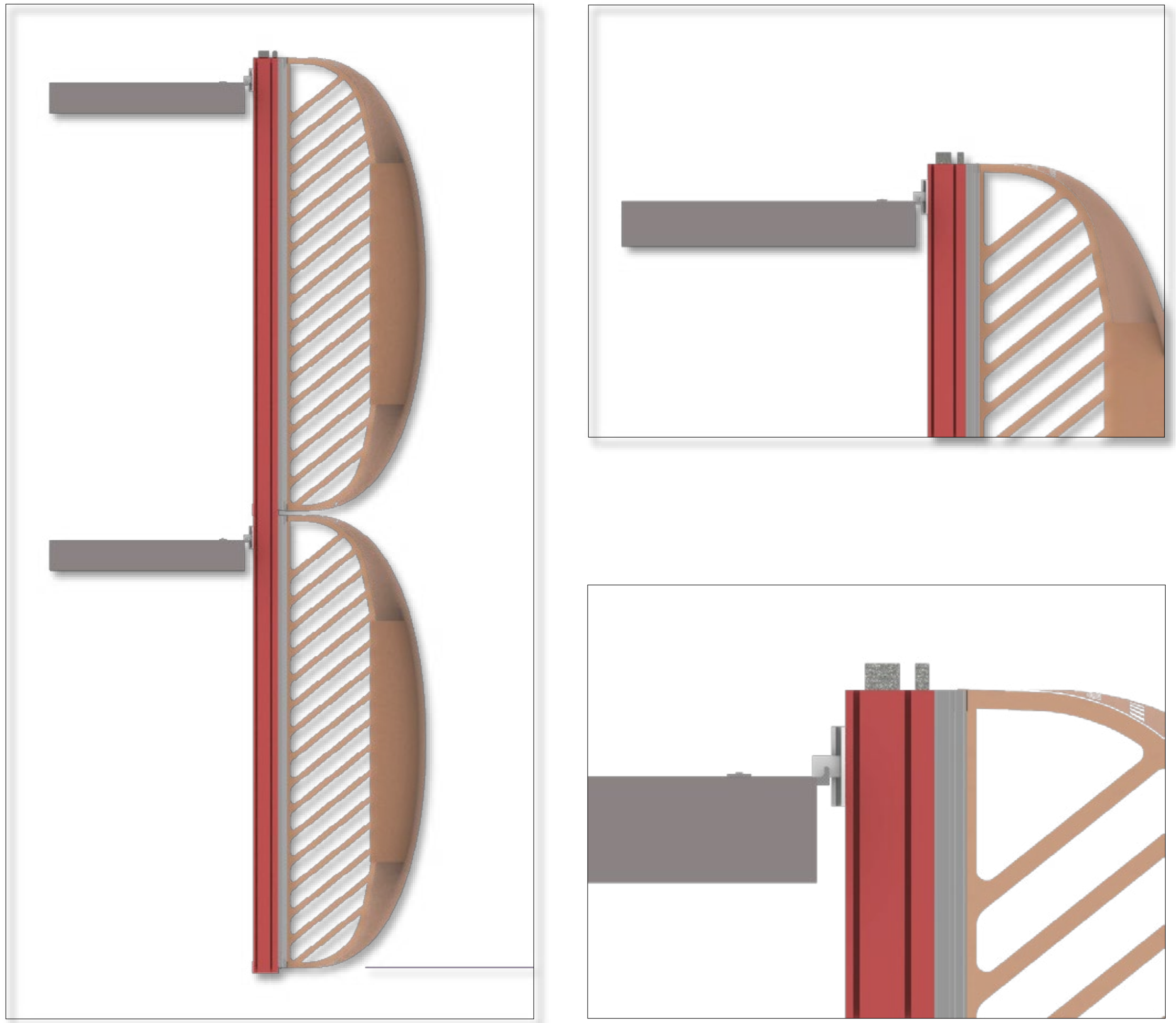


Figure 66. Side View Details

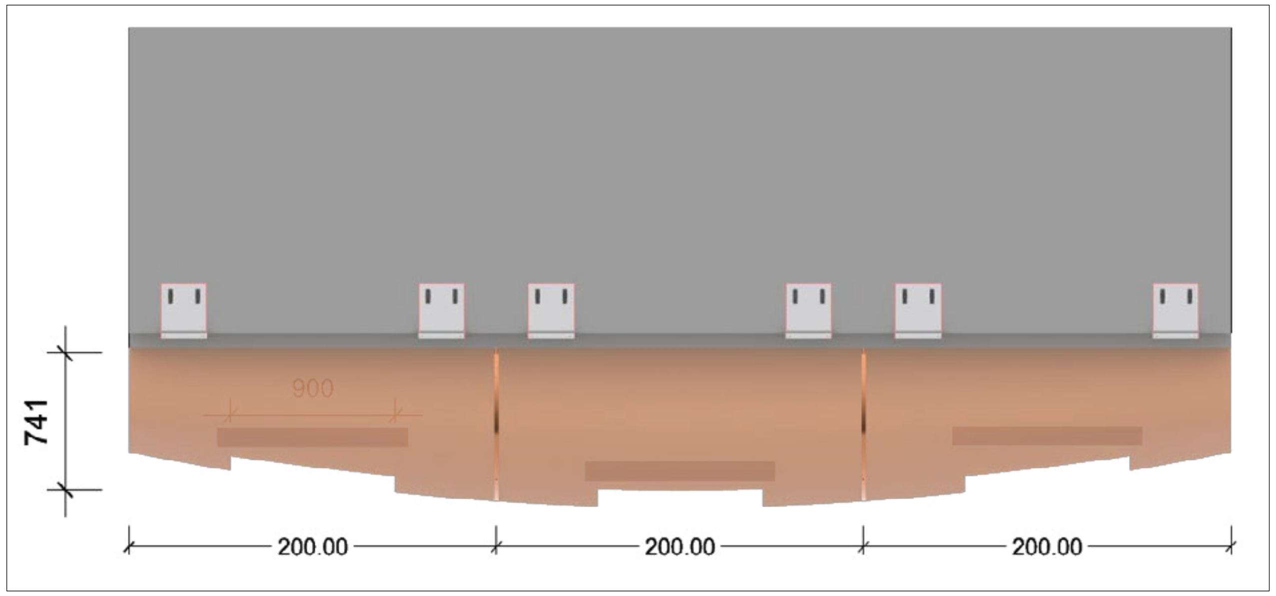


Figure 67. Top View

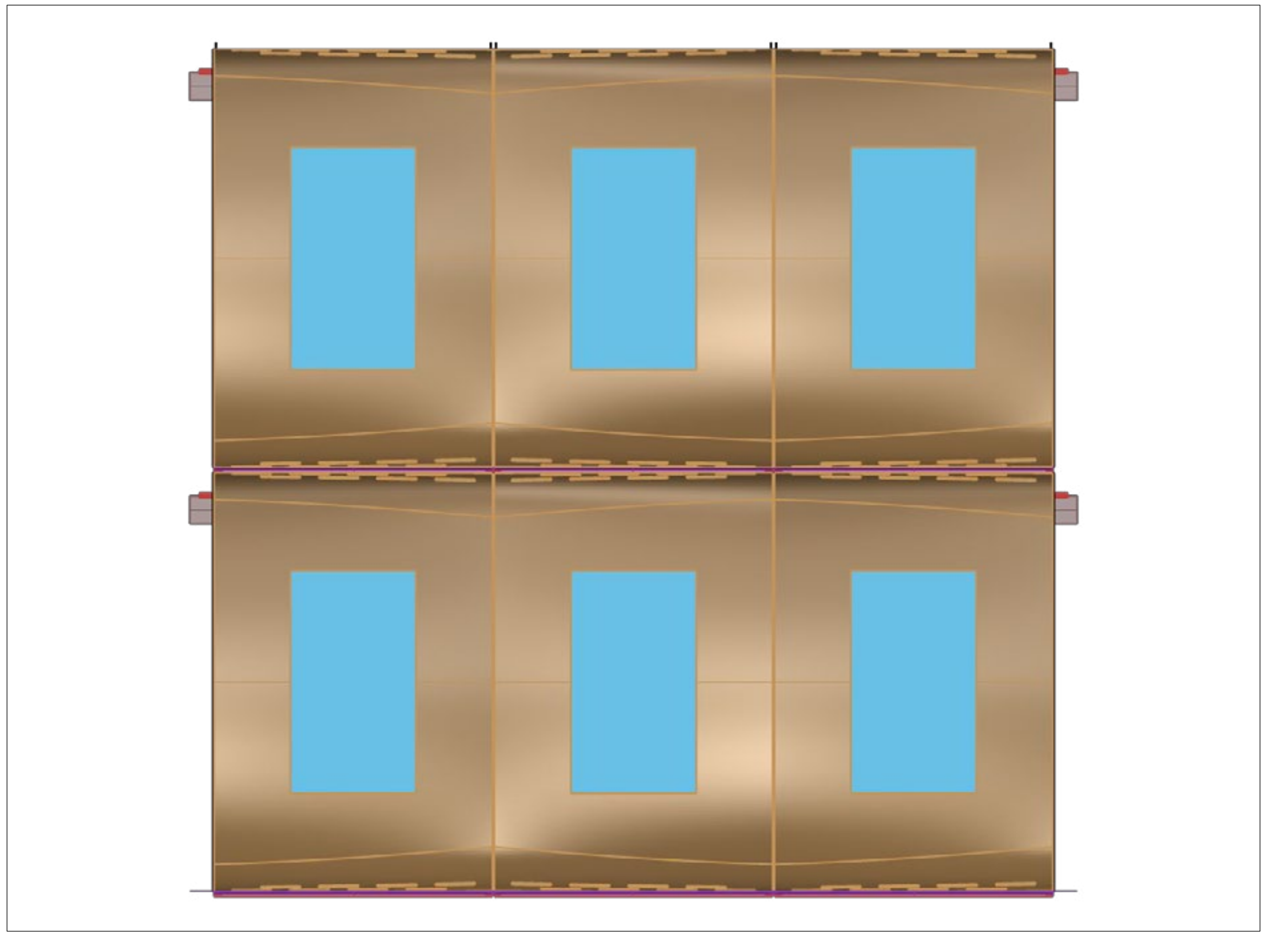


Figure 68. Font View

Figure 69. Perspective View of the developed façade

03. Façade Application Possibilities

03.1. Sandwiched Wall Panel

An interesting design opportunity for bio-based fiber reinforced composites is to be combined with other core materials to become a sandwiched panel. The panel could be applied on the façade of the building. To portray this idea, an example of an available was taken into consideration. “CIPEA Blockhouse by AZL Architects in China, was taken as an example to replace the available façade with bio-based fiber reinforced composites.

Figure 70. CIPEA Building

Figure 71. CIPEA Collage

In the figure above, a collage was made to show how the building will look if Flax/Bio-Epoxy replaced or covered the concrete walls of CIPEA façade. However, the challenge remains in insulating this material for several reasons, such as, climatical and structural challenges. To showcase more possibilities of how this could be applied, below are some options of a part of this building.

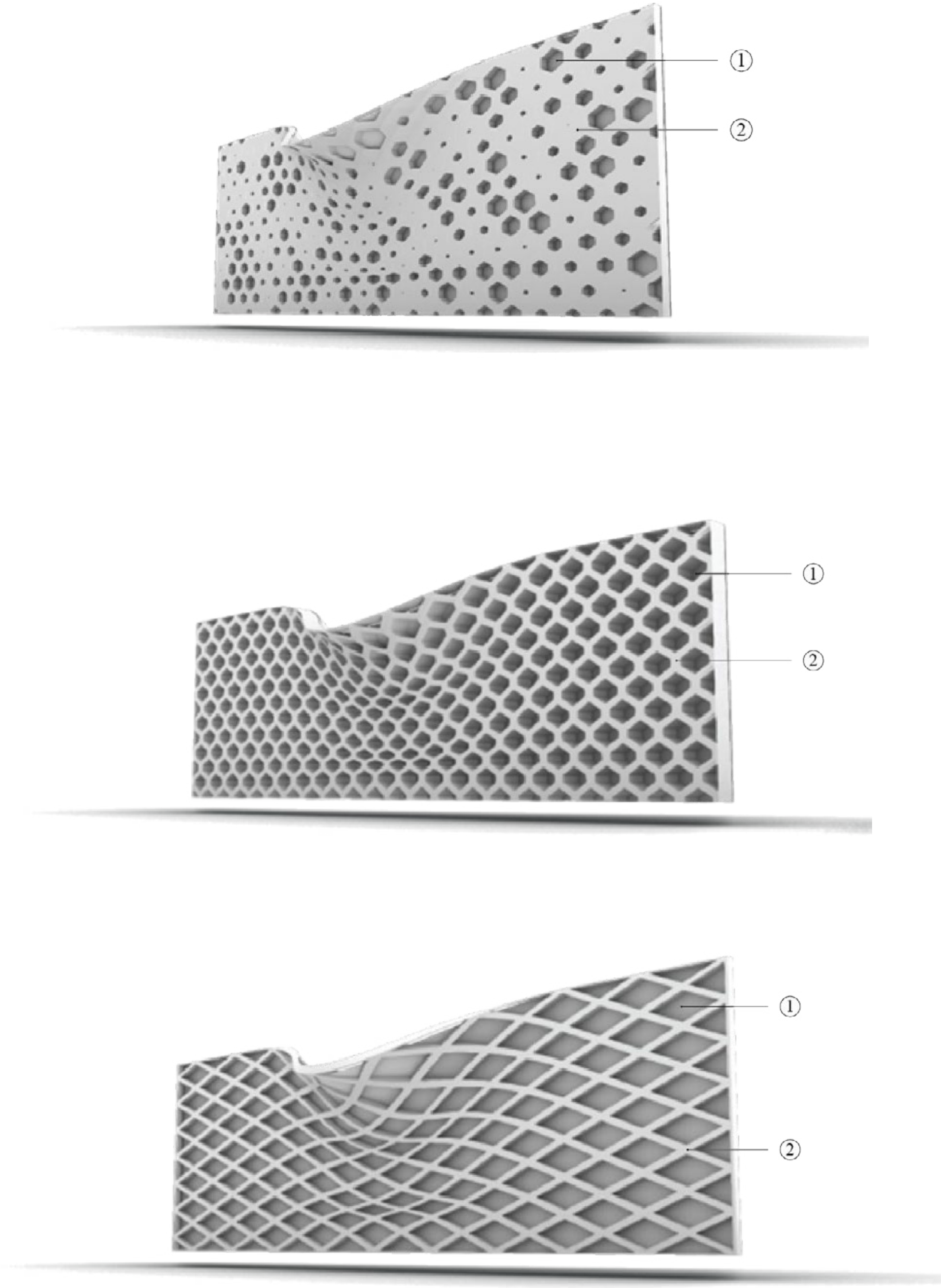


Figure 72. Core Possibilities

1- Flax/Bio-Epoxy Panel 2- Flexible hollow core material

3 variations of core materials were showcased in the previous figures. The core material applied on flax/bio-epoxy panels is better to be hollow (similar to honeycomb) so the translucency of the material does not get greatly affected. In case the bio-based panel includes a curve, the core material chosen must than have the ability to curve. Here are some possibilities for flexible core materials.

Figure 73. Core Material Possibilities

03.2. Cladding Material

Bio-based fiber reinforced composites has a potential to be used as a cladding material on facades. This is starting to become available in the market. For example, NPSP is designing a new cladding bio-based material. The client has the ability to decide on the shape of the panel and its color.

Figure 74. Cladding Material by NPSP

Figure 75. Cladding Material by NPSP 2

This example gives an idea of possible application of this material. The same concept could be applied using Flax/Bio-epoxy panel. This could be done using the same process of fabrication for flat panels which is the vacuum assisted resin infusion.

03.3. External Skins

A strong potential of the bio-based panel is to be used as an external skin of a double skin system. In this way, several aspects could be controlled during the design of the panel. For example, the patterns on of the panel could be modified to fulfill either some aesthetical needs, climatical needs, or privacy needs.

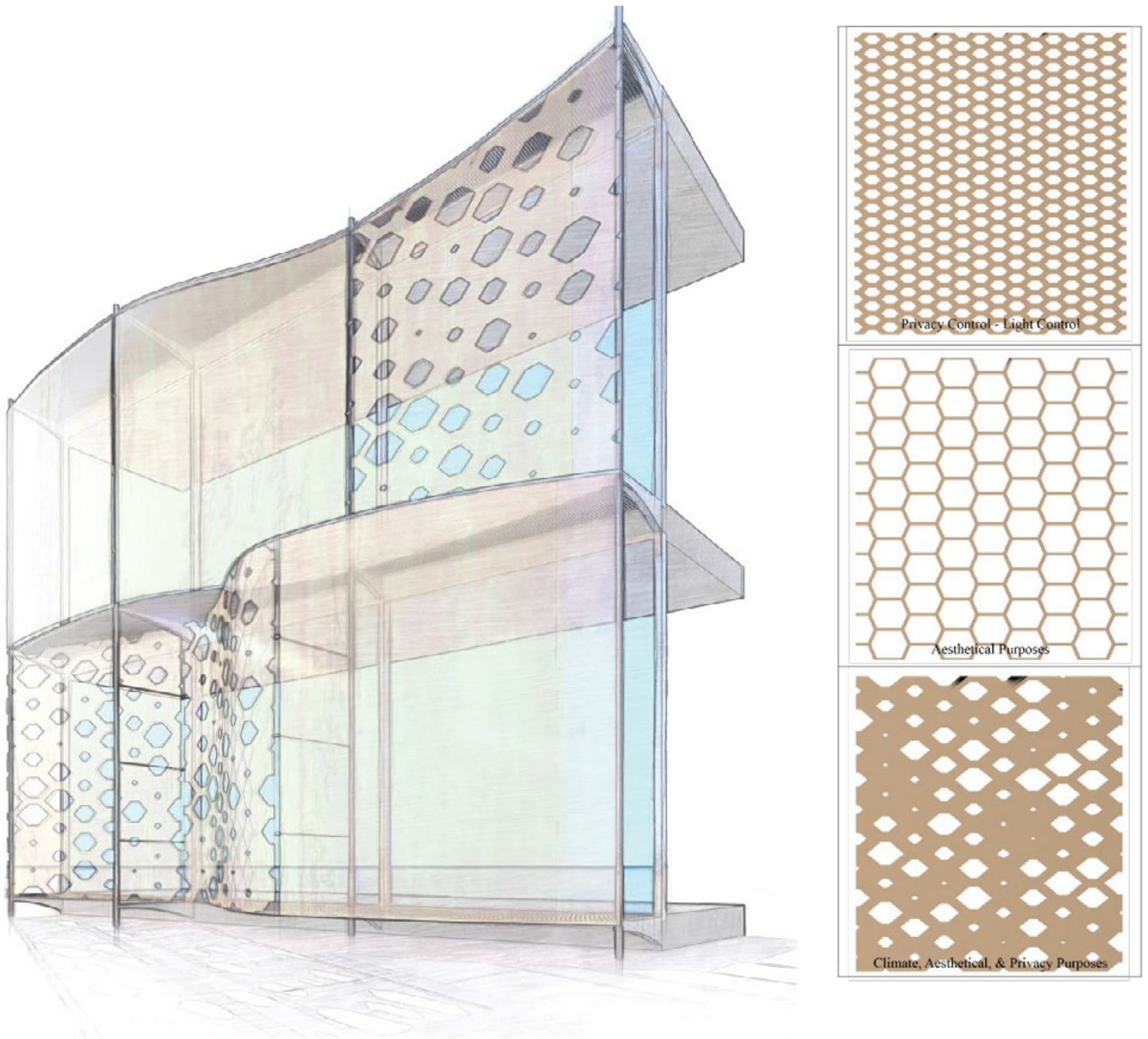


Figure 76. External Skin Possibilities

VIII – Conclutions & Future Recommendations

01. Conclusion

It exists a very wide range of possible mixtures when it comes to the fabrication of a bio-based fiber reinforced composite. Among this research, 21 possible choices of natural fibers were displayed (table 3). In parallel, a wide range of polymers exists, leaving the manufacturer with a thousand of options to explore.

It was crucial with the timeframe available for this research, to filter these materials following several aspects that greatly reduced the number of choices.

For fibers: Availability, cost, mechanical properties, and previous literature, showed that Flax and Jute are the natural fibers with the highest potential in composite manufacturing due to their wide availability in different arrangements (unidirectional, bidirectional – stitched, non-stitched - …)

	Density (g/cm^3)	**Moisture Content (%)**	**Tensile Strength (MPa)**	**Availability**
Flax	1.5	8	500	Easily found
Jute	1.3	9	600	Easily found

Table 46. Flax & Jute Properties

Matrices: Wide variety of thermoplastics and thermosets exist, however only few are extracted from bio-based sources. ‘Cardolite’, ‘Gruit’, ‘Resoltech’, ‘Sicomin’, ‘Braskem’are the famous european companies exploring the fabrication of bio-resins. Most of the advances are in Epoxies, and Polypropylen (PP). Knowing that the used resin for this research was epoxy, it was derived that the epoxy with the highest bio-source available in Europe is manufactured in France by the company ‘Sicomin’ with a ratio of 56% bio-based combining 6 carbons from vegetebale orgins with 4 carbons of petrol origins.

Before going into the details of fabrication and fiber/epoxy mixtures, it is important to know why are these materials important to explore and how do they compare to other fibers such as glass fibers and carbon fibers.

Figure 66. Stiffness Comparison Chart

Natural Fiber Reinforced composites are in general weaker than glass fiber and carbon fiber composites. This fact does not make them less important than glass or carbon fibers. With some modifications, natural fibers composites can be applied in the building environment same as glass fiber composites. In fact, and according to the litterature, using natural fibers reduces the cost and carbon footprint greatly.

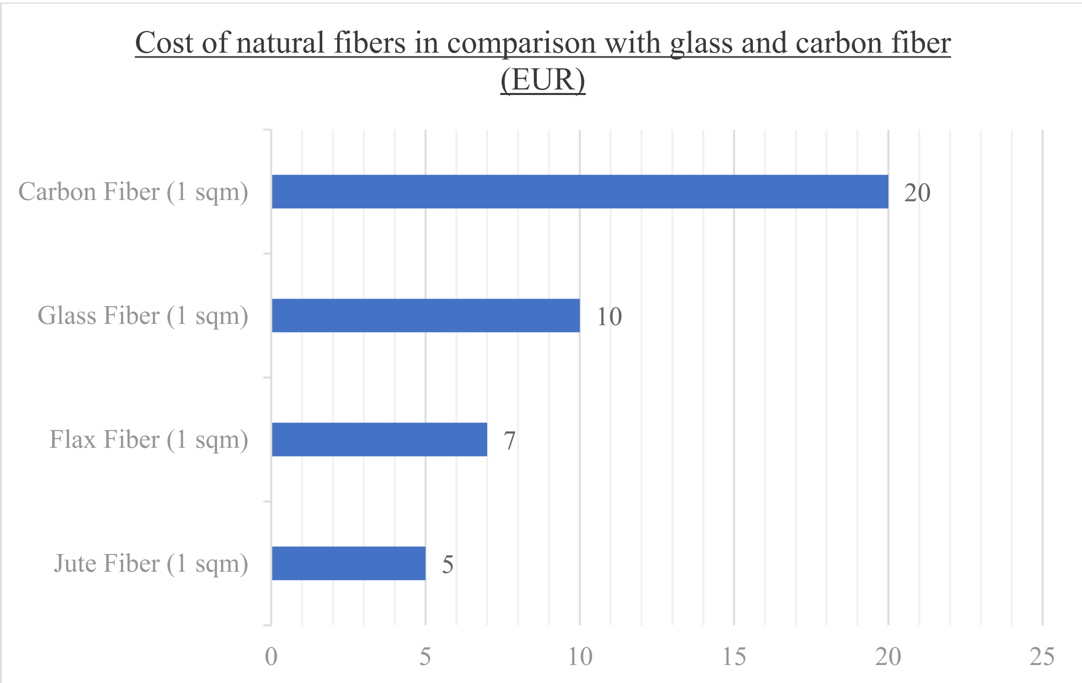


Figure 67. Cost Comparison Chart

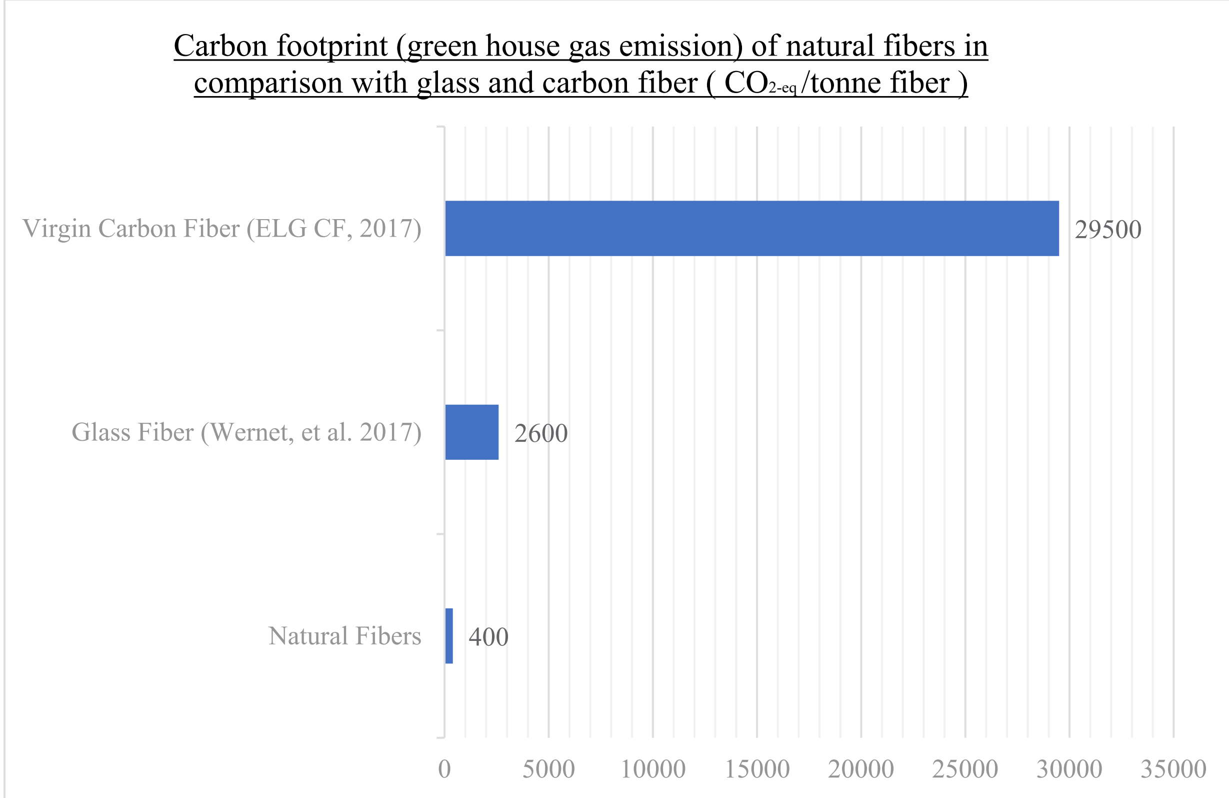


Figure 68. Carbon Footprint Comparison

After fabrication of the panels at TU Delft, using vacuum assisted resin transfer molding (VARTM) technique, the results showed that the material possess some aesthetical visual aspects that are worse investigating.

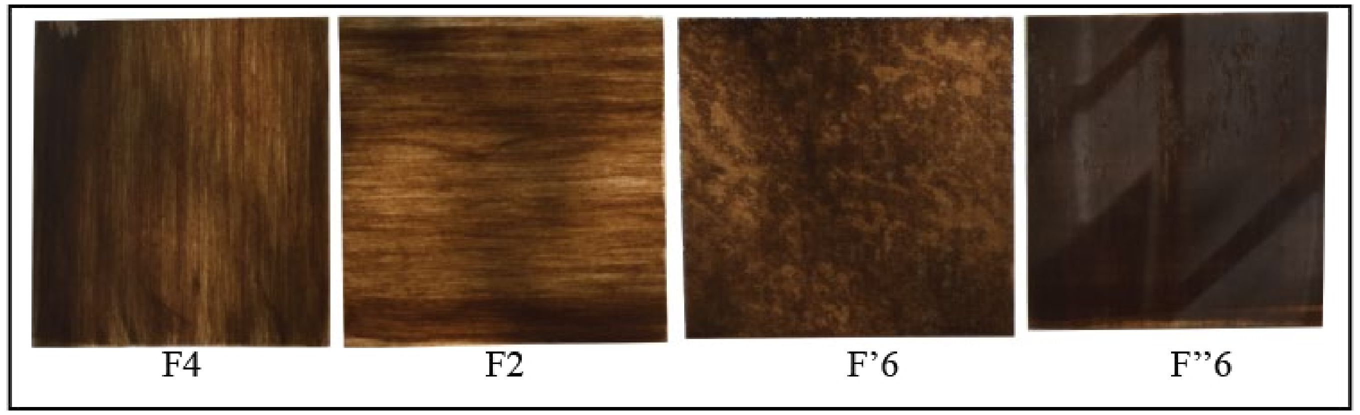


Figure 77. Panels Pictures

The material ressambles to wood with its color and appearance. Yet, it is reflective and translucent, and both of these aspects could be controled by modifying the number of layers, choosing the material of the mold, and choosing the releasing agent. However, after subjection to weathering conditions, the material aesthetical value was reduced, especially by water.

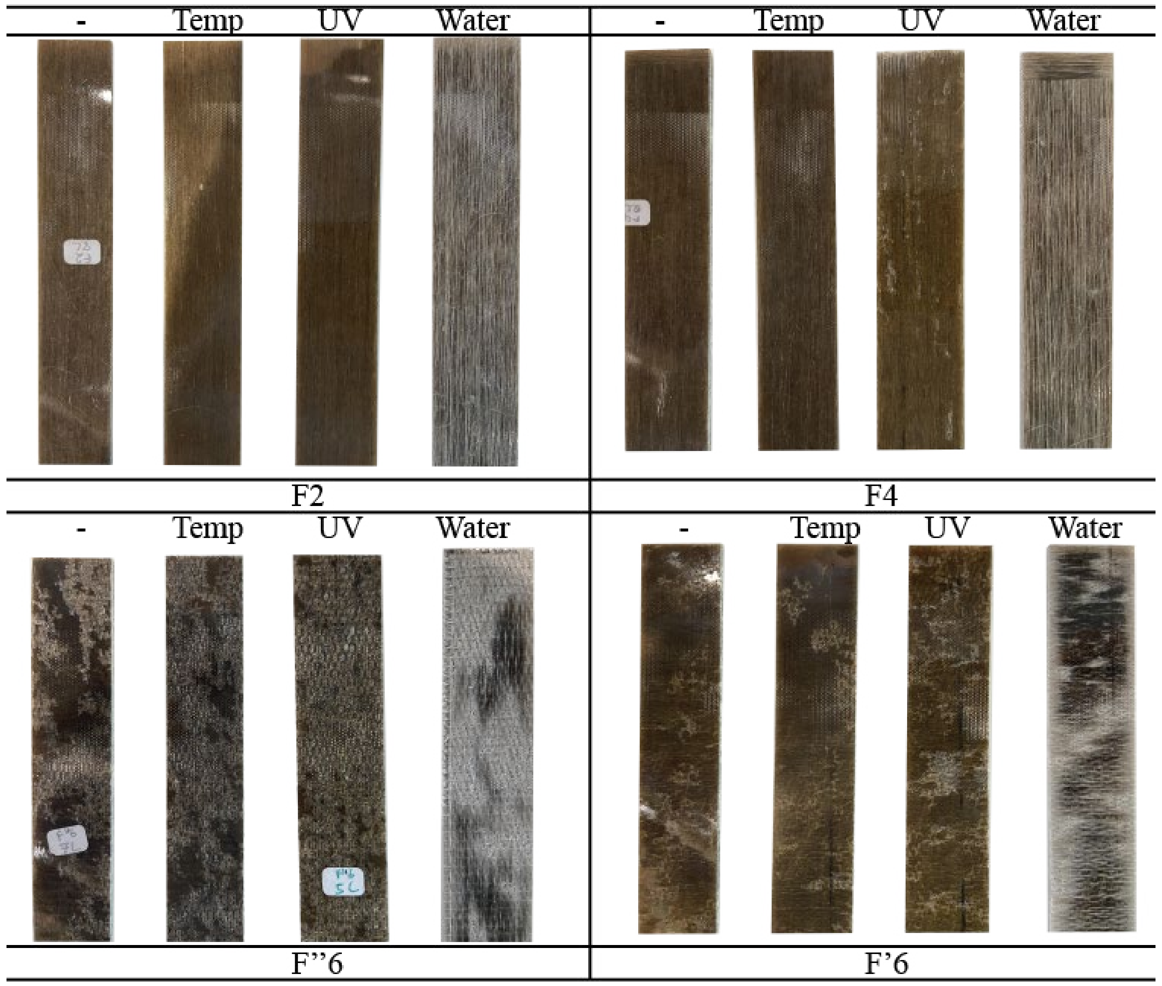


Figure 78. Panels Before & After Subjection to Weathering Conditions

Subjecting the material to water led to the loss of the protective epoxy layer on the front, which means that water will be absorbed by the fibers leading to failure later with time. Temperature does not seem to have any effect on the appearance of the material; however, UV light seems to give the material a visible yellowish surface that increase with time. Coating might be a solution for this problem, yet it is recommended to explore bio-based coating options if available.

As a method to validate the mechanical properties calculated from the bending and tensile tests of the fabricated flax fiber reinforced bio-epoxy, the conducted data was compared with the literature data.

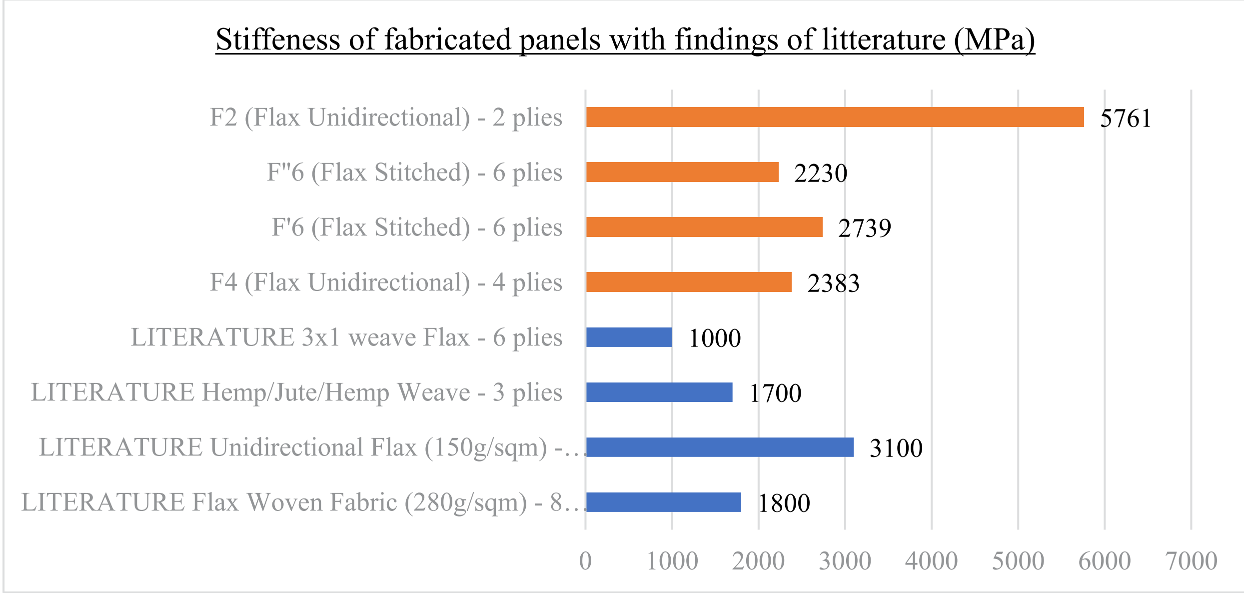


Figure 71. Stiffness of fabricated materials in comparison with literature review

The values in orange referring to the fabricated panels fall in the same range as the values in blue mapped from the literature. This comparison is important to check the validity of tests and experiments done during this research. When subjecting this material to weathering conditions, the mechanical properties are not greatly affected as seen in the chart below.

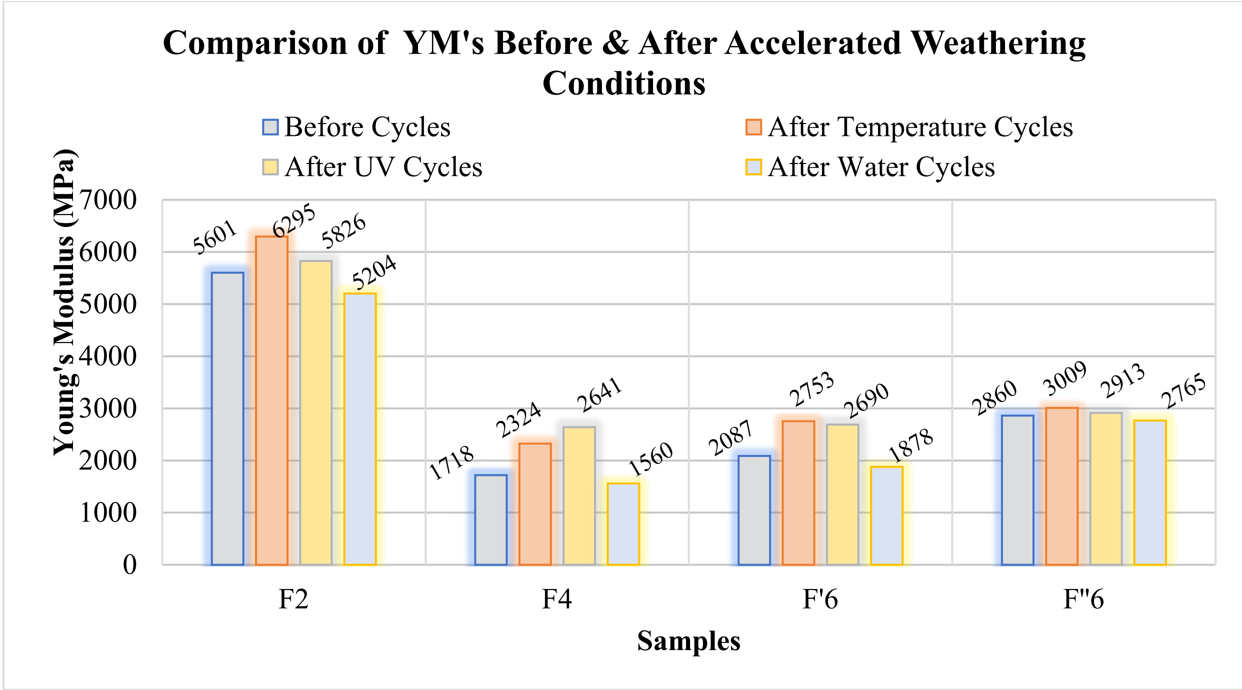


Figure 72. Comparison of mechanical properties before and after subjection to weathering conditions

However, water is considered the aspect decreasing the stiffness of the material, yet it is still a stiffness that is considered safe for design purposes as proven in the structural analysis.

An advantage of fabrication of this material is the ability to be fabricated in very big sized depending on the size of the mold. In addition to that, it could also be molded into any desired shape due to the fact that fibers are an organic material and epoxy is a liquid material that cure and solidify after fabrication. With the conducted data, and using the structural script for deflection on grasshopper, it is concluded that sizing the fabricated flax-reinforced bio-epoxy composite to a dimension of 2000 mm x 3000 mm is possible when including a curve in the geometry as seen in the figure below.

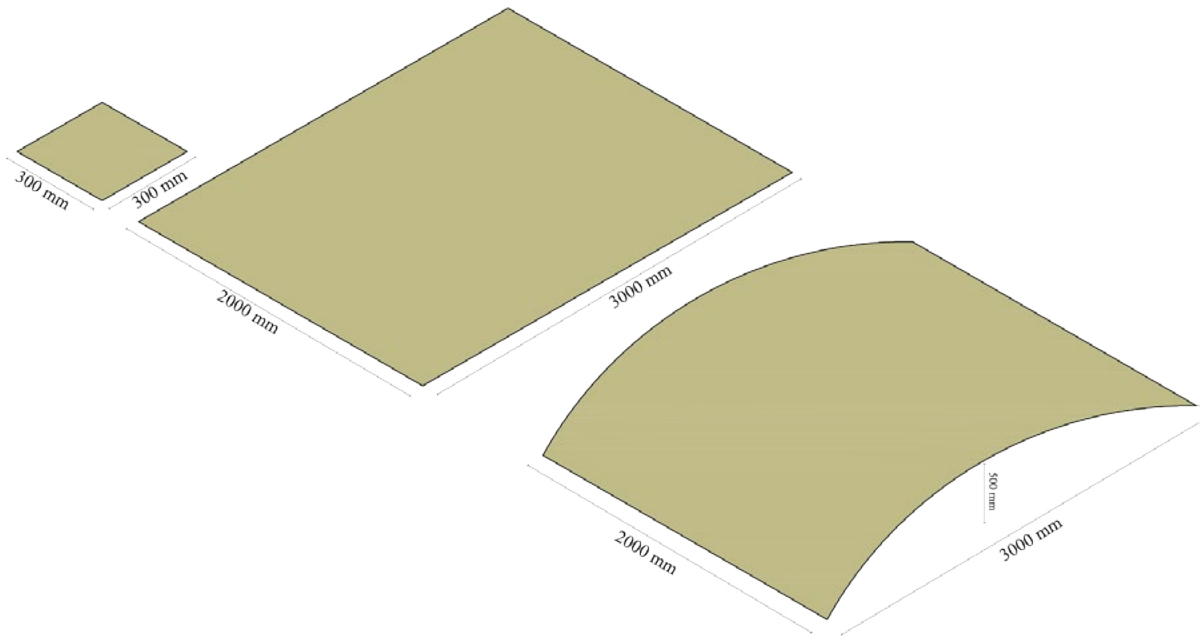


Figure 79. Sizing of Panel

Each of the panels F2, F4, F’6, and F’’6 showed different performance when subjected to wind loads. This performance was summarized by checking the serviceability limit stater, and the ultimate limit state of each of these materials in the following table

Panel	Thickness (mm)	Ultimate Tensile Strength (MPa)	Standard Deviation (Mpa)	Young's Modulus (Mpa)	Loads	Serviceability Limit State			Ultimate Limit State		
						Allowable Deflection (mm)	Deflection Y (mm)	Satisfied	ULS (Mpa)	δ_{max} (Mpa)	Satisfied
F2	1.2	165	31.5	5204	Wind + Weight	30	48.9	**NO**	51.52	2.5	**YES**
F4	3	74	11	1564	Wind + Weight	30	10.46	**YES**	25.44	1.1	**YES**
F'6	2.5	88	4.56	1878	Wind + Weight	30	15.04	**YES**	36.6	9.6	**YES**
F''6	2	96	11.56	2765	Wind + Weight	30	19.9	**YES**	35.02	1.5	**YES**

Table 47. SLS & UTS of panels F2, F4, F’6, F’’6

Using the script to interpret the results of the bending and tensile tests on a freeform shape was a very important step to validate the design of the panel to be applied on the building envelope. *(Any shape of panel could be connected to this script and checked for deflection when loads are applied (wind loads, self-weight).* As shown in the table above, with the panel design shown below, panels F2, F4, F’6, and F’’6 satisfy the serviceability limit state and the ultimate limit state.

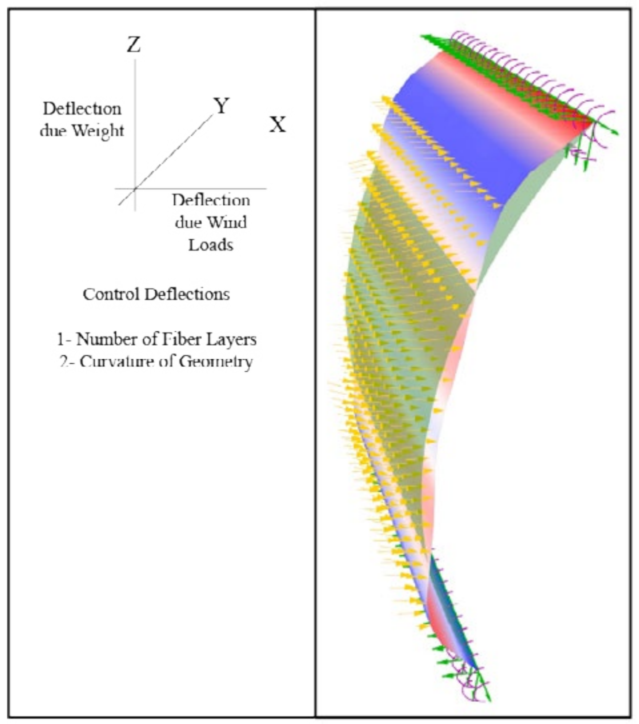


Figure 80. Structural Script Analysis Visualization

However, when adding weight to this panel *(weight of a window frame and glass)*, stiffeners on the both vertical edges are required. If not added, the material will deflect in the Z direction and will fail with time.

With this analysis, it is possible to apply this material on the building envelope with restrictions. For this research, it is concluded that the material can be applied as a rainscreen system, a cladding system, or an outer skin of a double-skinned façade system. An example of Flax-Fiber Reinforced Bio-Epoxy as an outer skin of a double skin unitized system is explored in this research

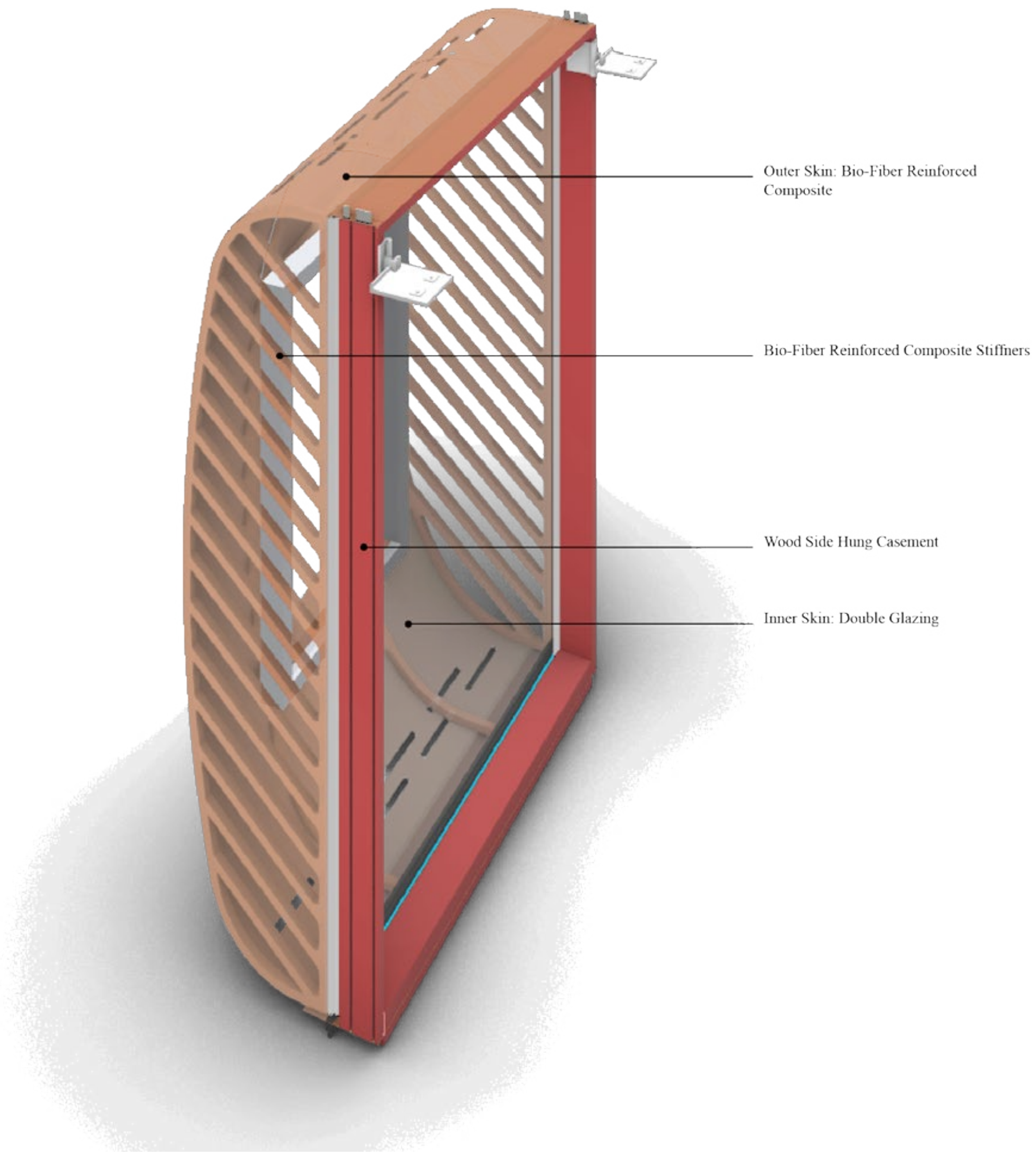


Figure 81. Unitized System Overview.

As a conclusion on the design, it is mostly important to note that there is a big variety of possible designs to be done using this material. However, it is the designer and client preference to decide on that and explore the potentials.

With the growing need of material independent from petroleum resources, Flax Reinforced Bio-Epoxy showed great potential in being a material worth investigating in the building industry and especially the building envelope. After testing, the material mechanical properties and structural performance proved the possibility of using it on the building envelope. It also proved that even on big scales, the material remains very lightweight and its embodied carbon is very low when compared with other composites such as glass and carbon fiber composites. Flax Reinforced Bio-Epoxy showed the ability to be curved and double curved due to its initial flexible state before curing. This allows the material to be advantageous on others and therefore worth of further investigation in other aspects.

02. Recommendations for further research developments

Flax/Bio-Epoxy composites showed a great potential in applications on building envelope, however there is still a lot of aspects to be researches and validated before application in real practice.

02.1. Fire Safety

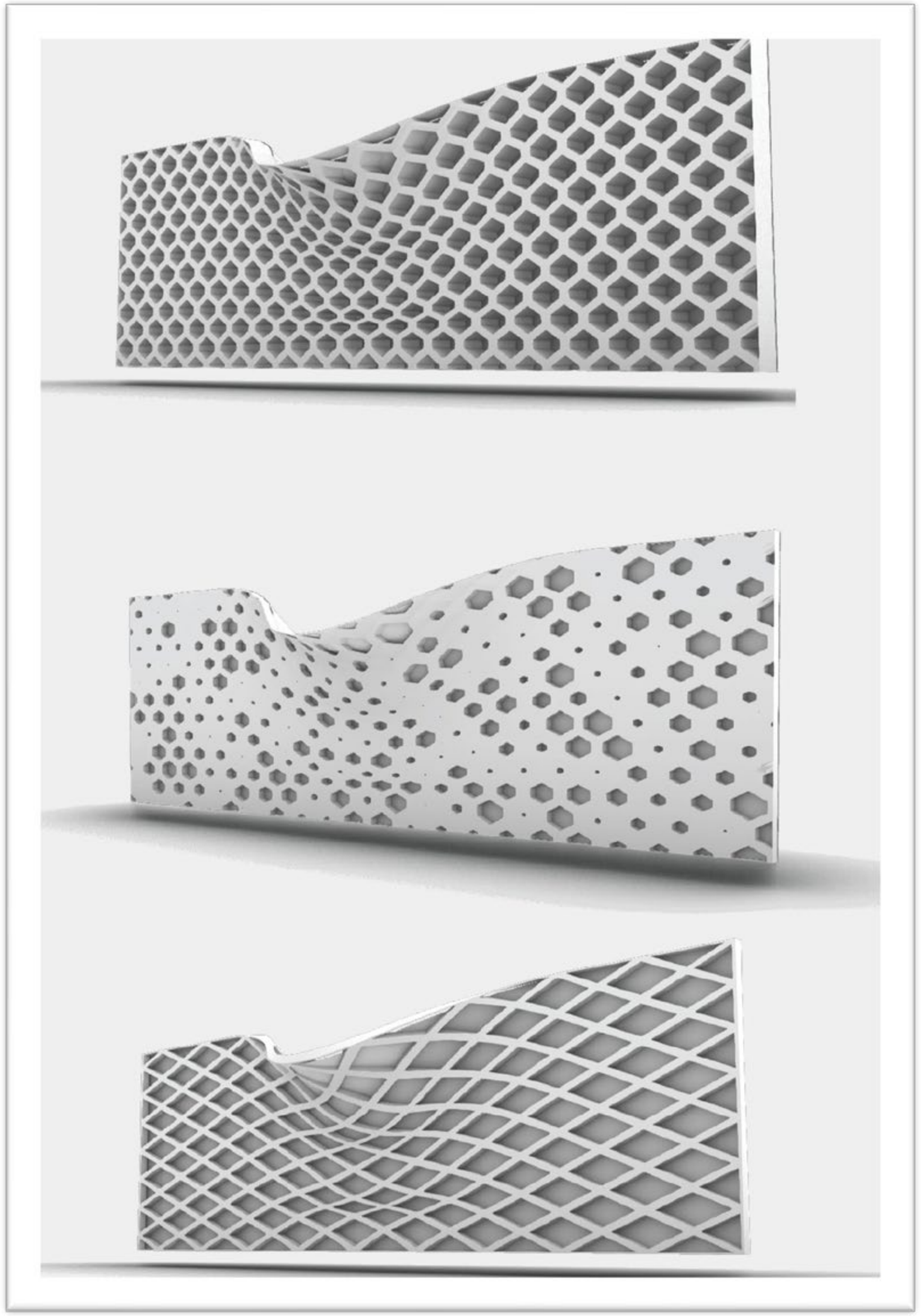
Fire Safety of this material needs to be checked before application

02.2. Coating of the surface

The material showed a very weak resistance to water in terms of aesthetical appearance. The solution for this issue would be by applying a protective coating layer. However, it is important to map and filter the availability of bio-based coatings and again investigate the material performance in front of weathering challenges.

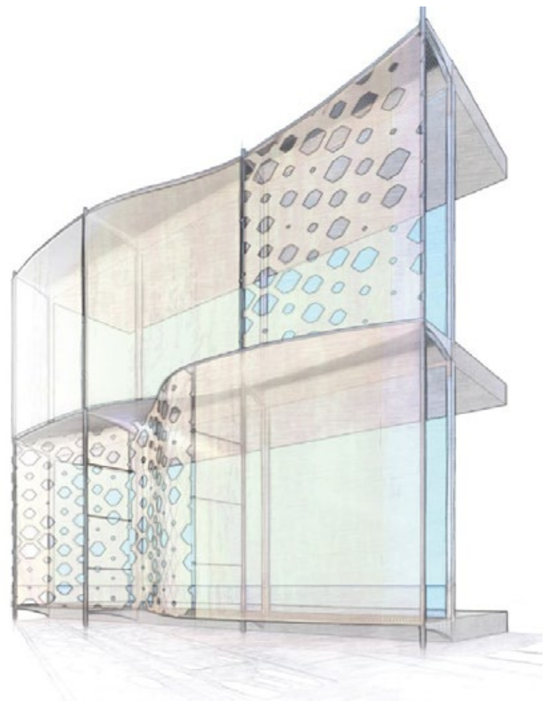
02.3. Flax/Epoxy as a sandwiched material

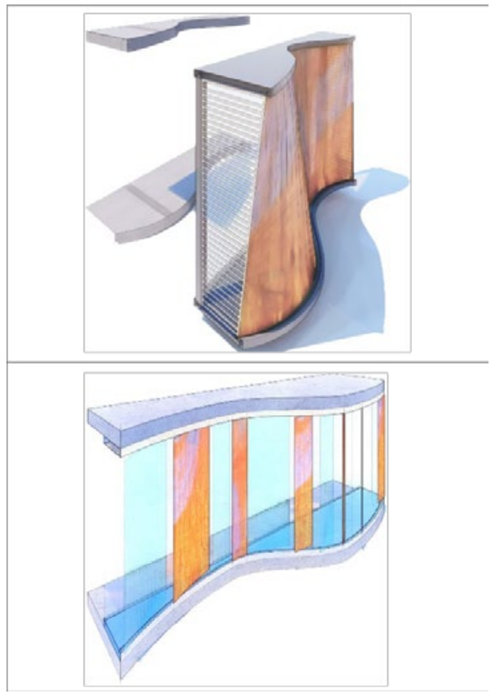
One of the options explored during the design phase was the use of the panels fabricated as a sandwiched materials and combine them with bio-based cores. This bio-based core should allow the entrance of light so the material won't lose its translucency. Some initial sketches are shown below.



02.4. Design Variations

As mentioned in the conclusion, the design proposed for double skin systems is only 1 in a thousand of options. Therefore, it is important to explore more options such as the shown below.





IX - Reflection

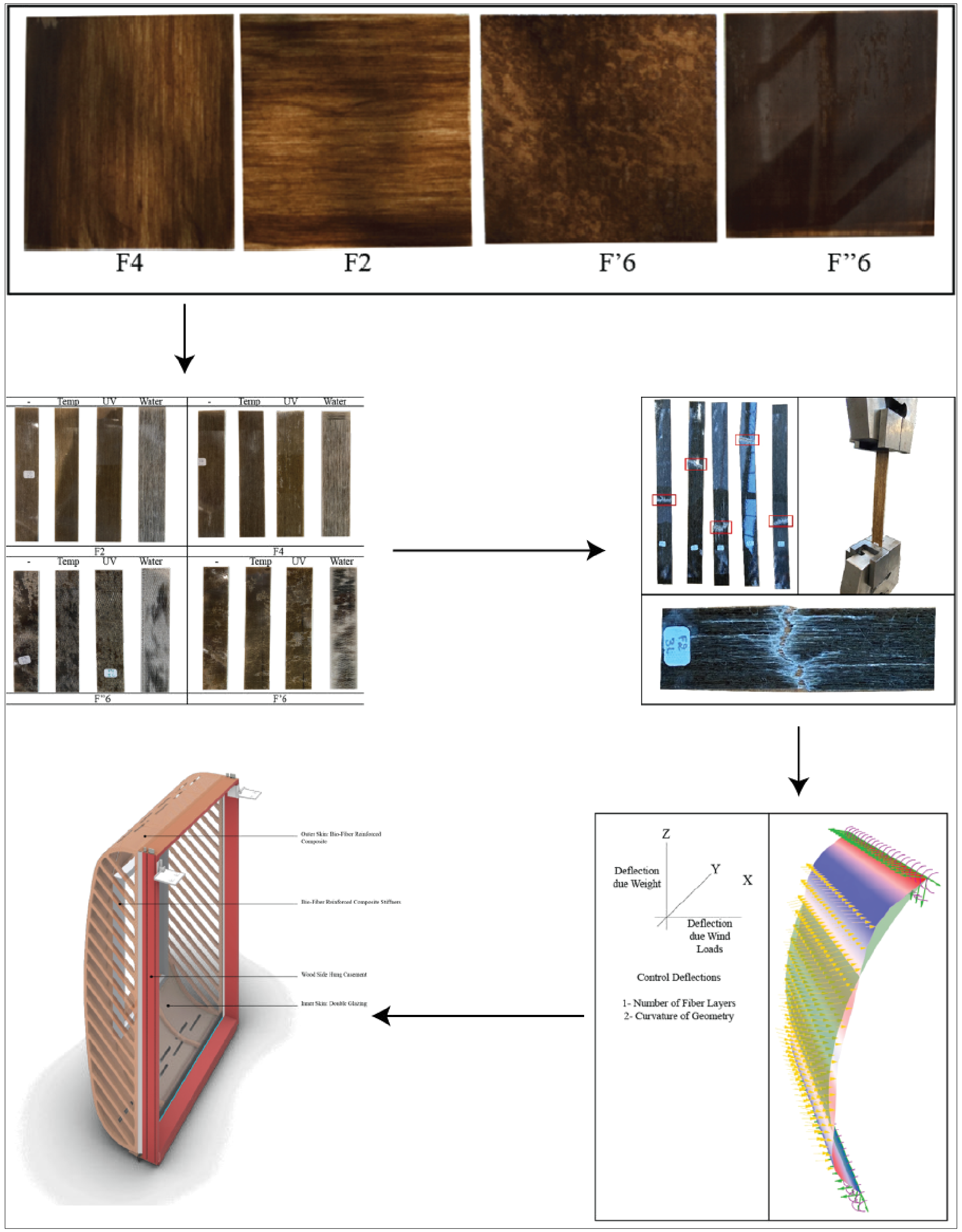
01. Graduation Process

01.1. Position of Graduation Topic in Studio

The graduation topic being titled "Bio-Based Composites & Possible Façade Application" is considered related to the studio through its relevance to all the challenges of the built environment that were discussed and studied during the master track of 'Building Technology', and in the graduation course manual. With the top one environmental challenge of shifting from petrol-based products to bio-based products, it becomes crucial to investigate, test and analyze new materials for the built environment. Bio-Based Composites is a topic that is still in its early developments, however it shows a great potential under the title of "Next Generation Material". For that, the topic is well positioned under The fields of Material Science, Structural Design, and Façade Design, which are considered an important pillar of the graduation studio.

01.2. Research Approach Development: Why and How?

My research approach was divided into two part "Research by Experimentation" and "Research by Design". Through the research by experimentation, all the related sectors to composite materialization and fabrication were investigated (fibers, resins, manufacturing techniques, fiber architecture). After filtering these findings, the labs experiments started, in which panels were fabricated and tested before and after weathering conditions at TU Delft. The reason for this approach is to provide approved and valid data that could be used to analyze the real performance of Bio-Based Composites. Using the collected Data from the tensile, bending, and accelerated weathering testing, It was possible to start the second part of the research. It is "Research by Design". In this approach, the data, and the results collected were used to design a system that could be implemented on the façade. Therefore, the design is considered validated by the data gathered during the first stage. To visually illustrate the process, find below a diagram of the panels fabricated, the testing, the analysis, and finally the design. This will summarize the research approach and its corresponding process.



01.3. Research Approach Results

Following the time schedule that was set in the start of the graduation studio, the results were gathered on time. All the excel files of the testing data, and the fabrication procedure were documented, and were ready to be analyzed. With the data being gathered, the analysis became possible. The tensile and bending properties of the fabricated panels were calculated. And another set of panels were subjected to weathering conditions and tested again. A comparison between the two sets of the data was done. With that being mentioned, it could be concluded that the research by experimentation results were successfully achieved.

Regarding the Research by design approach, the design and its details were developed using the data from the research by experimentation phase. However, by designing, there is always a thousand available options, and there is always room for development and modifications according to the designer preference. In the case of this project, several design variations will be presented, but only one will be detailed.

01.4. Relation between Research and Design

As explained in the previous paragraph, the research and the design are strongly connected. The design of the proposed façade consists of the fabricated materials and the conducted data. Throughout the report, it is explained how the design was achieved directly from the analysis. In brief, a structural tool was designed to input the data found, and through that tool, the shape of the design was generated, and later modified for aesthetic, and climatic purposes.

The proposed shape of the façade designed was detailed following the values and the materials explained in the literature review, and fabricated in the experimentation phase.

01.5. Ethical Reflection & Encounters

My mentors, the staff of the model hall provided me with full support throughout my research. The feedback sessions were very productive, and it was a pleasant experience. In addition to that, I received answers to all my question from other staff that helped me with the access to the testing machines, and the analysis of the data gathered.

02. Societal Impact

02.1. Applicability of Results in Practice

The findings of the research, especially the fabrication and experimentation part could be used by any person that want to design or prototype using Bio-Based Composites. For that, the results are considered applicable in practice. In terms of design, the double-skin façade system created is also relevant in terms of detailing and materialization. In practice, most construction & engineering companies are searching for new sustainable material to be applied in the building environment, and to replace the petrol-based materials that are immensely increasing in price, and harming for the environment. For that, investing in such research leads to the development of a new material that could be applied in practice, and used in the market.

02.2. Extent of Innovation Achievement

Bio-based Fiber Reinforced Composite is a material that is newly investigated in the built environment. Through this research, suggestions on how can it be applied on the building envelope were provided. The provided option in this research is to apply this material as an outer skin of a double skin system, which is a concept that was never applied before, but shows a high potential if investigated furtherly. It was also proved through this research, the possibility to use this material in freeform designs. It was shown that the material can be double curved, which is an innovative outcome for organic applications. It was also shown that the material is up 70% bio-based, which is an innovative outcome for the composite market.

02.3. Contribution to sustainable development

As mentioned in the introduction of this research, same outcome could be achieved using glass-fibers composites and carbon-fibers composites, however those materials are petrol-based and possess a higher embodied carbon than bio-based options. Usually, composites used on buildings consists of petrol-based resins, and petrol-based fibers. In this research the resin used "Sicomin Greepoxy" is 56 % bio-based and the fibers are 100% natural (Unidirectional Flax),

completely coming from plants and seeds. With that being said, the research is strongly contributing to the sustainable development with today's environmental challenges.

02.4. Impact of project on sustainability

The project is suggesting a sustainable application for the building environment using bio-based fiber reinforced composites. Following the results of this suggesting the material has a potential to positively impact the sustainable environment. However, there is a very big number of aspects that still need to be checked in order to completely prove that this project has a complete positive impact on sustainability. Some of these aspects to be furtherly researched are the coating of this material to improve its performance against weathering conditions. Since the system is bio-based, it is important to investigate bio-based options for that matter. Another aspect to be investigated is the fiber architecture before manufacturing. It is possible to provide more options for the fiber arrangements. And finally, the possibility to combine this material with another bio-based core, in order to create a sandwiched bio-based panel.

02.5. Relation between Project and Social Context & Its effect on the built environment

With the increasing environmental awareness in the building sector, and the challenge of the building industry to adapt to the European Union's development strategies and environmental challenges, it is relevant for society to investigate new non-wood bio-based materials, and find a way to use it as a replacement of petroleum/fossil-based materials. Investigating in that area could have a positive impact in response to today's environmental challenges both on a social level, and on a scientific level. On a social level, the research investigated, provided data, and analysed a product with a reduced embodied energy, and environmental-friendly, yet with comparable properties as conventional materials. The research could be considered as a base for further researches on bio-composites applications, for that it is considered to have a positive relation with the social context.

The research showed a new example of construction using a new sustainable material. It also proved the potential of this material in terms of shaping, reduction in weight, and comparable mechanical properties with other conventional materials already used in the built environment. It could be therefore concluded that the research effected the built environment by showcasing a new example in exploring the “next generation materials”, and their design potential.

X- References

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XI – Tables & Figures

01.Figures

02. Tables

XII – Appendix

01. Summary of Chemical, Physical, & Mechanical Properties of Commonly Used Fibers

		Chemical Composition of commonly used Fibers						Physical & Mechanical Properties of Fibers									
		Cellulose (wt%)	Hemi cellulose (wt%)	Lignin (wt%)	Pectin (wt%)	Wax (wt%)	Ash (wt%)	Density (g/cm³)	Length (mm)	Diameter (µm)	Cell Wall Thickness (µm)	Lumen Width (µm)	Moisture Content (%)	Tensile Strength (MPa)	Elongation at Break (%)	Young Modulus (Gpa)	Reference
Bast	**Hemp**	70-77	18-20	3.7-5.7	0.9	0.8	0.8	1.5	5 - 55	20.0	-	-	6-9	580 - 1110	1.5-4	70	(Douglas, 2014)
	Jute	61-71	14-20	13-12	0.2	0.5	0.5-2	1.3	2 -5	26-30	-	-	9.0-12	187 - 773	1.5 – 3.1	13 -26.5	(Douglas, 2014)
	Flax	71-81	18-20	2.0-3.0	2.2-2.3	1.5-1.7	1.5	1.5	9 - 70	20.0	-	-	8	350-1100	1.2 - 3	27.6	(Douglas, 2014)
	Kenaf	45-57	44	8.0-13	3.0-5.0	0.8	2.0-5.0	1.4	2 - 6	21.3-28.6	6.2-6.9	8.0-16	9.0-12	223-930	2.7 – 6.9	53	(Lau, 2017)
	Ramie	68-76	13-16	0.6-0.7	1.9	0.3	0.0	1.5	60 - 260	8.0-20	2.8	12.8	7.5-17	400-1000	1.2-3.8	44-128	(Douglas, 2014)
Leaf	**Abaca**	56-63	20-25	7.0-9.0	1.0	0.0	3.0	1.5	4.0-6.0	17-21	-	-	7.0-15	418-813	3.0-10.0	31-33	(Lau, 2017)
	Pineapple	81.0	7.1	12.0	0.0	0.0	2.0	1.5	3 - 9	5.9-6.31	1.8-2.15	2.4	9.0-13	400-1627	1.0-3.0	60-82	(Lau, 2017)
	Sisal	66-78	10.0-14	8.0-14	10.0	2.0	0.6-1	1.5	1 - 5	-	-	-	9.0-11	400-700	1.9 - 3	9.0-22	(Douglas, 2014)
	Banana	63-64	12.1	5.0	0.0	0.0	2.0	1.4	-	-	-	-	8-12.0	529-914	3.0 - 10	27-32	(Lau, 2017)
Fruit/Seed	**Cotton**	85-90	5.7	0.7-1.6	0.0	0.6	0.0	1.6	20 - 54	-	-	-	8-8.5	287-800	7.0-8.0	5.0-13	(Douglas, 2014)
	Oil Palm	50-63	80.0	20.5	0.0	0.0	0.0	0.18-1.32	-	-	-	-	70.0	60-81	8.0-18	1.0-9.0	(Lau, 2017)
	Coir	32-43	0.15-0.25	40-45	3.0-4.0	1.0-2.0	2.7	1.2	50- 300	270.0	-	-	8.0-10	108-252	15-30	4.0-6.0	(Douglas, 2014)

01. Summary of Chemical, Physical, & Mechanical Properties of Commonly Used Fibers

		Chemical Composition of commonly used Fibers						Physical & Mechanical Properties of Fibers									
		Cellulose (wt%)	Hemi cellulose (wt%)	Lignin (wt%)	Pectin (wt%)	Wax (wt%)	Ash (wt%)	Density (g/cm³)	Length (mm)	Diameter (µm)	Cell Wall Thickness (µm)	Lumen Width (µm)	Moisture Content (%)	Tensile Strength (MPa)	Elongation at Break (%)	Young Modulus (Gpa)	Reference
Cane/ Grass	**Bamboo**	26-43	30.0	21-31	0-0.2	1.0-2.0	1.7-5.0	1.3	2.0-2.4	-	-	-	8.8-8.9	140-230	4.0-7.0	11.0-17.0	(Lau, 2017)
	Bagasse	33-55	17.0	18-25	0.0	0.0	1.7-1.8	1.2	-	-	-	-	8.8-10	222-290	1.1-4.0	20-27	(Lau, 2017)
Wheat	**Wheat**	28-45	15-31	15-20	0-1	0.5-1	6.0-8.0	0.7-1.0	1.14-1.18	13.6-19.3	439.0	5.7	5.1-8.3	55.0	2.0-5.0	22.0	(Lau, 2017)
	Rice	38-57	19-33	8.0-20	10.0-15.0	14-17	10.0 - 20.0	0.6-0.8	0.9	1.7	-	-	8-9.1	10-200	2.7	1.0-12.0	(Lau, 2017)
Wood	**Balsa**	40-45	23-26	25.0													(Ashori, 2010)
	Alder	44.1	77.2	22.0													(Ashori, 2010)
	Birch	45.4	84.2	17.7													(Ashori, 2010)
	Beech	46.7	35.8	20.7													(Ashori, 2010)
Others	**E-Glass**	-	-	-	-	-	-	2.5		5.0-24				2000 - 3400	2.5	73	(Mahltig, 2018)
	S-Glass	-	-	-	-	-	-	2.5		3.8 - 20				4700.0	5.3	86	(Mahltig, 2018)
	Carbon	-	-	-	-	-	-	1.6		5.0-10				3790.0	11.0	240	(Mahltig, 2018)

02. Properties of Commonly used Thermoplastics

	Properties of Commonly Used Thermoplastics Matrix										
	Tensile Strength (MPa)	Young Modulus (MPa)	Elongation at Break (%)	Izod Impact Strength (J/m)	Tg (ºC)	Tm (ºC)	Td (ºC)	αT (mm/mm/ºC x 10^5)	Density (g/cm³)	Water Absorption (%)	References
Thermoplastics											
Low Density Polyethylene (LDPE)	12	200	90-500	854	65	95	32-50	10	0.91	0.01	https://polymerdatabase.com/
High Density Polyethylene (HDPE)	26	1400	840	27-1068	-120	130	43-60	10-20.0	0.96	0.01-0.2	https://polymerdatabase.com/
Polycarbonate (PC)	61	2200	50	700	180	260	420	65	1.15	0.1	https://polymerdatabase.com/
Polypropylene (PP)	26-41	1300	15-200	21-267	-10	175	50-63	6.8-13.5	0.92	0.01-0.02	https://polymerdatabase.com/
Polystyrene (PS)	46	2800	1-2.5	17	100	110-135	83	6.0-8.0	1.04	0.03-0.10	https://polymerdatabase.com/
Polyvinyl Chloride (PVC)	48	2200	10-100	32	80	180	67	6.0-8.0	0.7-1.35	0.1-0.4	https://polymerdatabase.com/
PSUL	70.2		75	6.5 kj/m2	188	63	480	-	1.35	0.335	https://polymerdatabase.com/
Polymethylmethacrylate (PMMA)	75	2800	4.5	24	105	160	90	-	1.185	2	https://polymerdatabase.com/
PEEK	100	3600	50	5.7 kj/m2	143	343	260	-	1.30	10	https://polymerdatabase.com/
PSS	82.7	2400	4	-	59	146	130	9	1.36	-	https://polymerdatabase.com/

03. Bio-based Epoxy & Epoxy Availability Information

	Bio-Based	Bio-Based Diluent	Name	phr	Bio-based	Mixture Percentage	Bio-content source	Amine type	Supplier	Glass Temperature	E'g (Mpa)	σ yt	Elong at B	Reference
Formulite 2500A	yes	yes	LITE2002LP	51	Yes	46.8	CNSL	Aromatic	Cardolite (Belgium)	72	2000	48	4.3	https://www.vosschemie-benelux.com/
Formulite 2500A	yes	yes	Formulite 2401B	30	Yes	36.6	CNSL	Cycloaliphatic & aromatic	Cardolite (Belgium)	99	2610	68	4.9	www.vosschemie-benelux.com
SuperSap INR	yes	no	SuperSap INS	33	No	19	PO	Cycloaliphatic & aromatic	Entropoxy Res (USA- Spain)	118	2380	67	4.2	https://www.pecepoxy.co.uk/
AMPRO BIO	yes	no	AMPRO BIO SLOW	29.3	Yes	40	CNSL, PO	Cycloaliphatic & aromatic	Gurit (UK)	66.5	1940	42	7.9	https://www.gurit.com/AMPRO
1800 ECO	yes	yes	1804 ECO	26	No	33	PO	Cycloaliphatic & aromatic	Resoltech (France)	59.3	2460	37	3.8	www.scabro.com
Greenpoxy 56	yes	yes	SD 8822	31	No	43	PO	Cycloaliphatic & aromatic	Sicomin (France)	75.1	3100	72	3.6	www.sicomin.fr
Greenpoxy 56	yes	yes	SD 8824	21	No	42	PO	Cycloaliphatic & aromatic	Sicomin (France)	78.4	3030	65	5.7	www.sicomin.fr
Infugreen 810	yes	yes	SD 8822	31	No	29	PO	Cycloaliphatic & aromatic	Sicomin (France)	75.4	3010	75	3.6	www.sicomin.fr
Infugreen 810	yes	yes	SD 8824	22	No	31	PO	Cycloaliphatic & aromatic	Sicomin (France)	81	2620	61	6.8	www.sicomin.fr
Non-Bio Based Epoxy														
LY556	no	no	HY917		no				Huntsman	151	2900	88	4.7	https://www.generaladhesivos.com/
DER 331	no	no	IPD		no				Dow	162	-	58	4.7	https://www.palmerholland.com/
LY556	no	no	D230		no				Huntsman	96	-	67	5	https://www.generaladhesivos.com/
LY 556 HDGE	no	no	HE600		no				Huntsman/dow/Evonik	127	-	-	-	https://adhesives.specialchem.com/
LY 556 HDGE	no	no	IPD		no				Huntsman/dow/Evonik	133	-	-	-	https://adhesives.specialchem.com/

04. Available Data on Non-Wood Natural Composites

Fiber Reinforced Thermoplastics	Matrix	Fiber	Fiber Content wt %	Fiber Treatment	Manufacturing Method	Mechanical & Thermal Properties					References
						Young's Modulus (Mpa)	Flexural Strength (Mpa)	Tensile Strength (Mpa)	Impact Strength (KJ/m2)h	Elongation at Break	
Sisal + PP	PP - dstiff 770 ADXP	Sisal	35	None	Extrusion	**4600**	**75**	**-**	**27**	**-**	Kaewkuk, 2012
Sisal + PP	PP+UT+MAPP	Sisal	30	Alkali	Injection molding	**-**	**-**	**28**	**16**	**9**	Oksman, 2008
Sisal + PP	PP	Sisal	40	Maleic Anhydride	Compression Molding	**4565**	**-**	**80**	**10.2 Nm/cm2**	**2.75**	Kaewkuk, 2012
Jute + LDPE	LDPE	Jute	Sheets	Alkali Silane	Compression Molding	**900**	**28.8**	**27.7**	**-**	**5.1**	Sever, 2010
Jute + PP	PP - Adstiff 770 ADXP	Jute	33	MAPP	Extrusion	**5800**	**69**	**-**	**20**	**-**	Kaewkuk, 2012
Hemp + PP	PP	Hemp	30	5NaOH-5MAPP	Compression Molding	**1800**	**49**	**29**	**-**	**-**	Mishra, 2007
Hemp + PP	PP	Hemp	40	Maleic Anhydride	Compression Molding	**4174**	**-**	**-**	**14 Nm/cm2**	**2.75**	Sullins, 2007
Flax + PP	Eltex-PHV200	Flax	30	2.5 VTMO	Injection Molding	**2500**	**48**	**28**	**-**	**-**	Kandola, 2020
Flax + PP	PP - Adstiff 770 ADXP	Flax	38	None	Extrusion	**6200**	**79**	**-**	**21**	**-**	Oksman, 2008
Banana + PP	PP - Adstiff 770 ADXP	Banana	33	None	Extrusion	**3300**	**43**	**-**	**15**	**-**	Mishra, 2007
Banana + PP	PP	Banana	40	Maleic Anhydride	Compression Molding	**3245**	**-**	**334**	**15.5 Nm/cm2**	**2.5**	Oksman, 2008
Kenaf + PP	PP	Kenaf	30	None	Compression Molding	**1410**	**29.34**	**15.83**	**14.5**	**-**	Bernard, 2011
Coir + PP	PP	Coir	30	diazonium salt in pH	Injection Molding	**3600**	**56**	**28**	**56 j/m**	**-**	Ali, 2012
Doum + LDPE	LDPE	Doum	20	Alkali	Extrusion	**370**	**-**	**10.2**	**-**	**42**	Arrakhiz, 2013
PineApple Leaf + PP	PP	Pineapple Leaf	30	None	Compression Molding	**2010**	**45.25**	**17.07**	**14.8**	**-**	Ng, 2018
Wood Fiber + HDPE	HD2090 3MAPE	Wood Fiber	50	None	Extrusion	**3183**	**-**	**28.7**	**42**	**-**	Paridah, 2015
Flax + Epoxy	Formulate SI	Flax	4 layers	None	Hand Lay-Up			**53.9**		**2.7**	Dhakal, 2019

05. Hand Lay-Up & VARTM Epoxy/Natural Fiber Composites

Fiber Type	Direction	Number of Plies	Process	Resin	Tensile Strength (Mpa)	Youngs Modulus (MPa)
Unidirectional Flax (180 g/sqm)	0	10	VARTM	Epoxy	265	10300
3x1 weave Flax	0	6	Hand Lay-up	Epoxy	90	1000
Flax Woven Fabric (280g/sqm)	0	8	Vacuum Bagging	Epoxy	90	1800
Unidirectional Flax (150g/sqm)	0, 90, 0, ...	16	Hand Lay-Up	Epoxy	80	3100
Hemp/Jute/Hemp Weave	0	3	hand Lay Up + 25 Kgs Compression	Epoxy	120	1700
Basalt / Flax	0	16	VARTM	Epoxy	298	17000

06. Fabrication Equipment

The materials needed to elaborate a vacuum assisted resin transfer molding are:

1- Vacuum Pump 150W with refrigerant Table Gauge is used to withdraw all the air from the composite and provide pressure during the curing time of the panel.

Figure 27. DANIU FY-1H-N 150W Vacuum Pump Air

www.banggood .com

2- Resin infusion catch-pot acts as a resin trap and sits between the vacuum pump and the infusion project to prevent resin accidentally being drawn into the vacuum pump

Figure 28. CP1 Resin Infusion Catch Pot 1.2L ECP Industrial

www.easycomposites.co.uk

3- 2x infusion tube line clamp used to block the passage of excessive resin at the end of the impregnation process. Also used to control the amount of epoxy infused.

Figure 29. Infusion Line Clamp

www.easycomposites.co.uk

4- 2x Resin Infusion Silicone Connector sits inside the vacuum bag and accepts a 9mm OD vacuum hose and has a slot underneath to feed into the resin infusion spiral.

Figure 30. Silicone Connector

www.easycomposites.co.uk

5- 6mm PVC Vacuum Hose used to feed the mold with resin in the resin pot and used to connect the end of the mold with the resin catcher.

Figure 31. PVC 6 mm Hose

www.easycomposites.co.uk

6- VB160 Vacuum Bagging Film LFT (1500mm width) used to completely close the mold and seal the fibers and the resins from air.

Figure 31. VB160 Vacuum Bagging Film

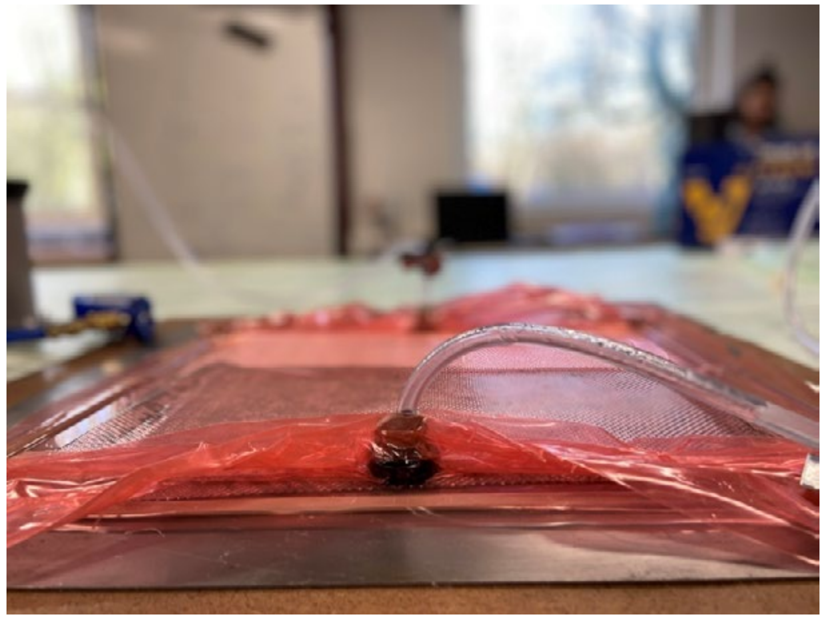
www.easycomposites.co.uk

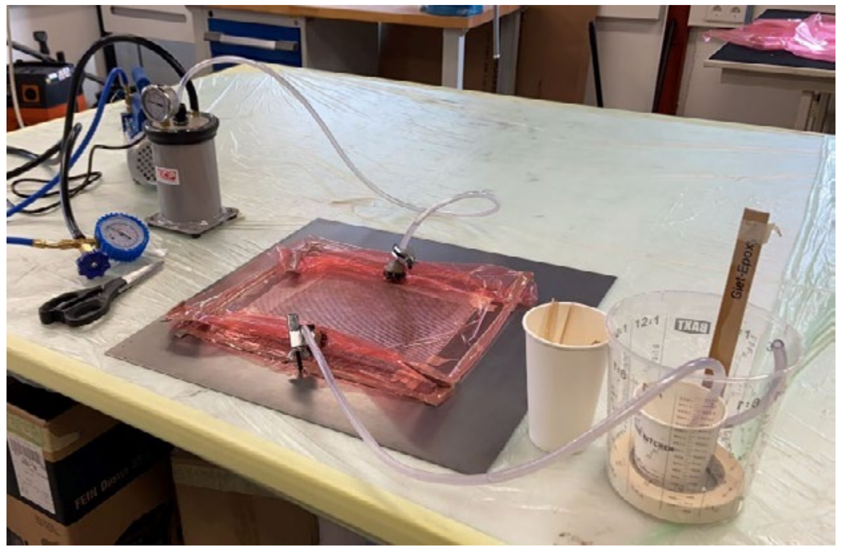
7- PP180 Economy Peel Ply Black Tracer used to create a textured surface on a laminate ideal for secondary laminating/bonding or to act as a porous, removable barrier between the laminate and other bagging consumables for processes such as resin infusion. Being a porous layer, peel ply allows the vacuum to bleed trapped air and volatiles out of the laminate and so finds applications in wet-lay vacuum bagging, resin infusion and some prepreg laminating.

Figure 31. PP180 Peel Ply

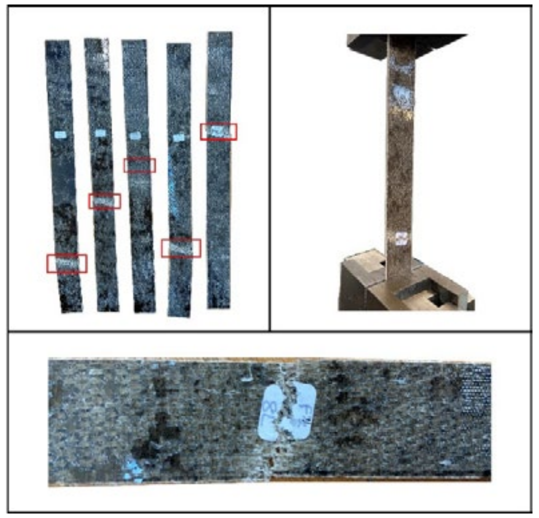
www.easycomposites.co.uk

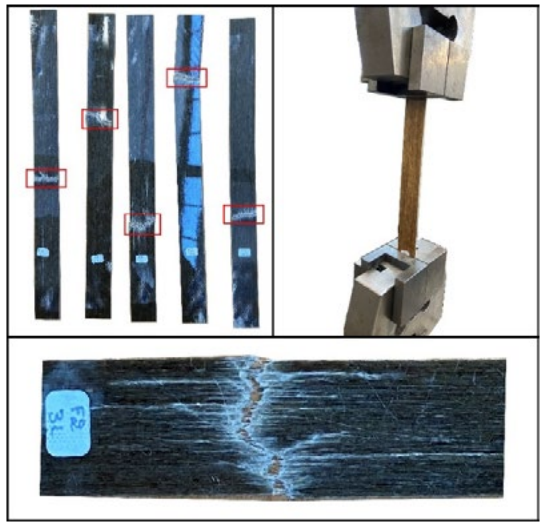
07. Fabrication Procedure

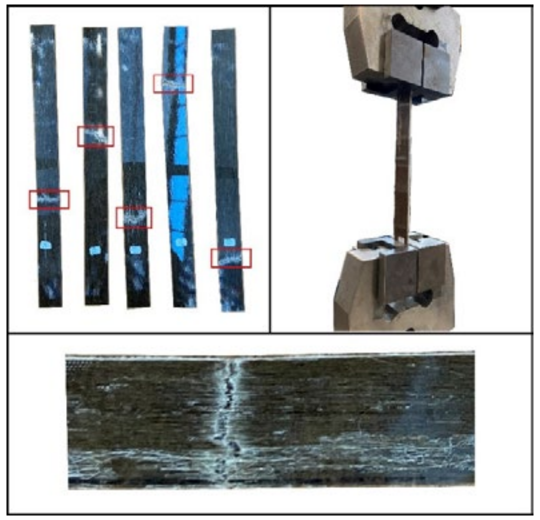


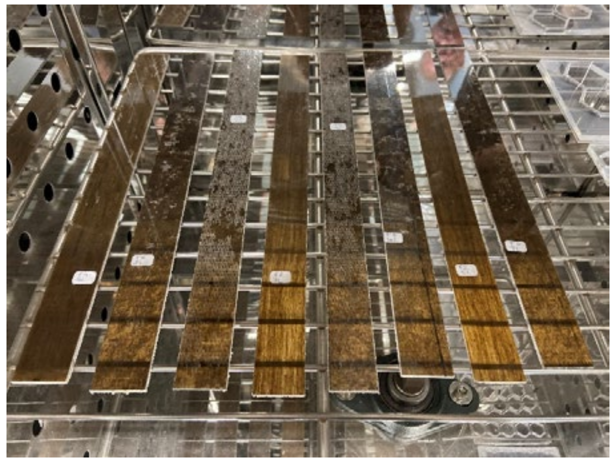


08. Testing of Materials



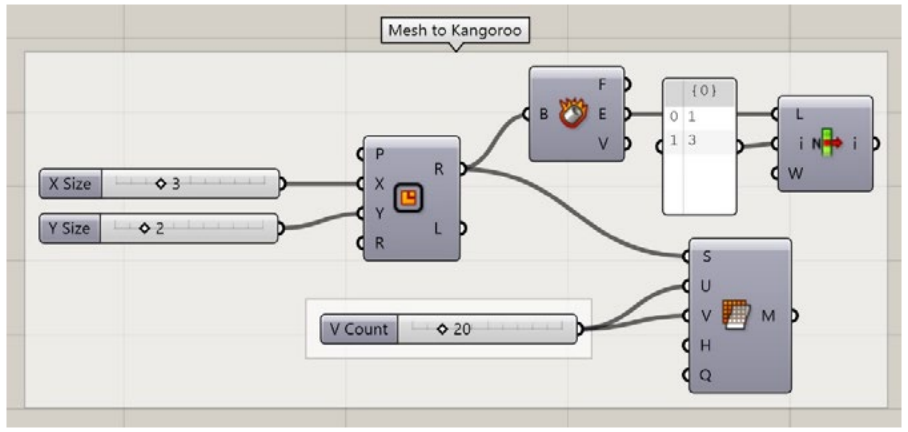




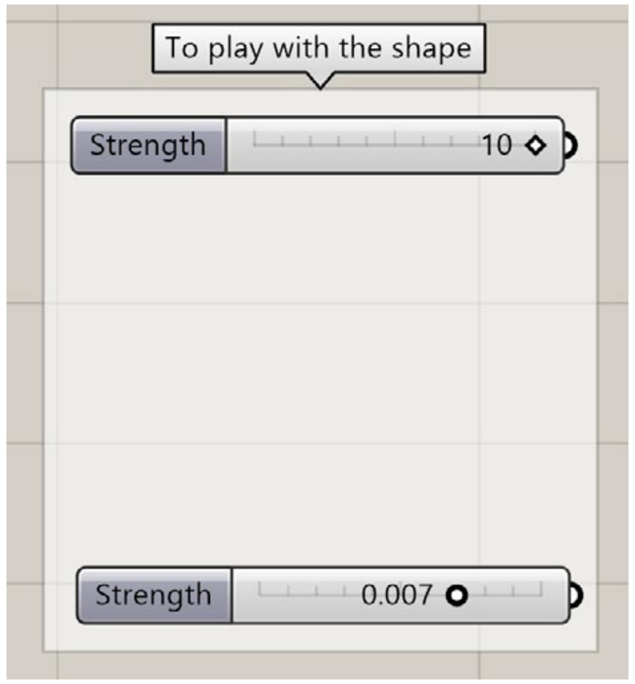


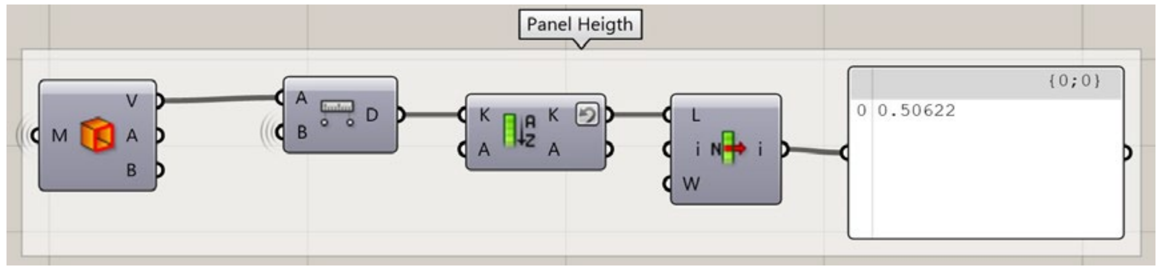
09. Structural Script

09.1. Mesh Input

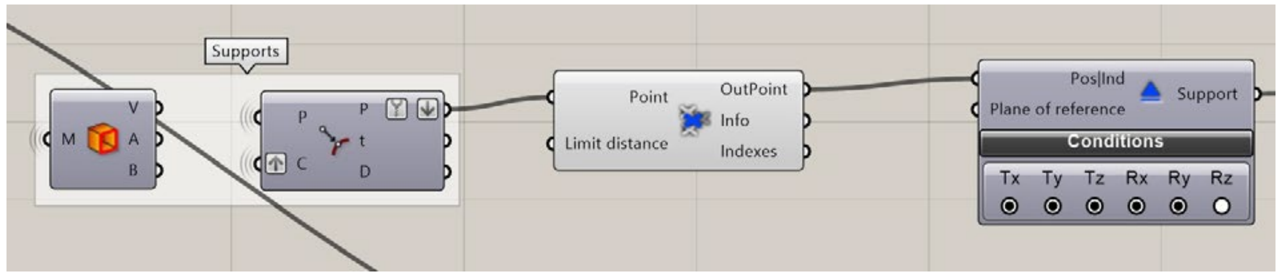


09.2. Curve Modification & Measurements of Curve

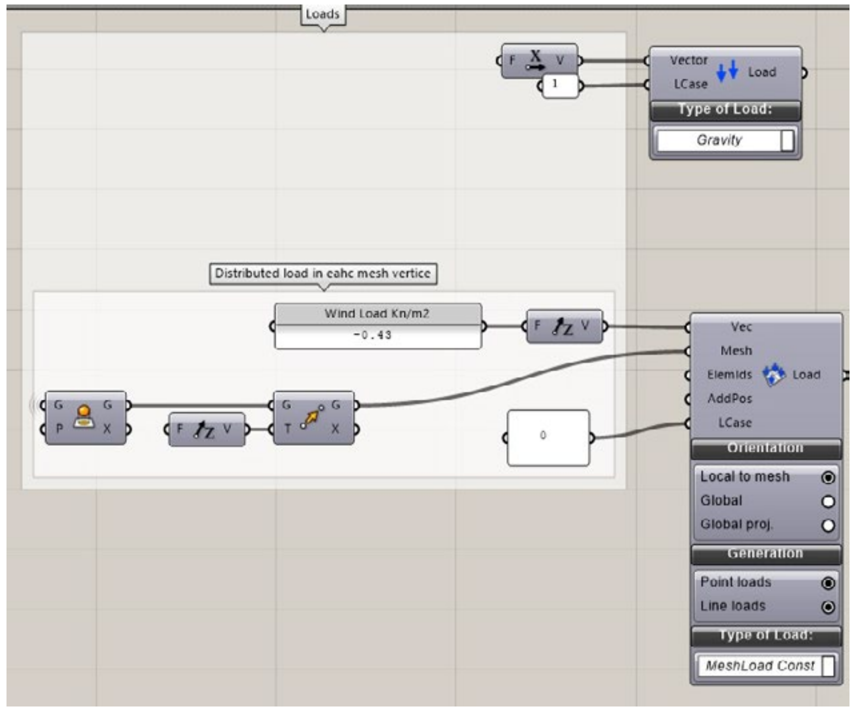




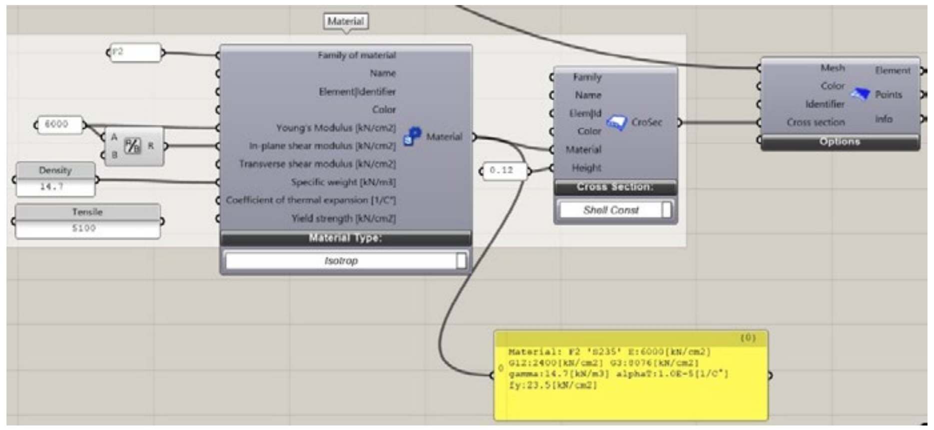
09.3. Adding Type of Supports



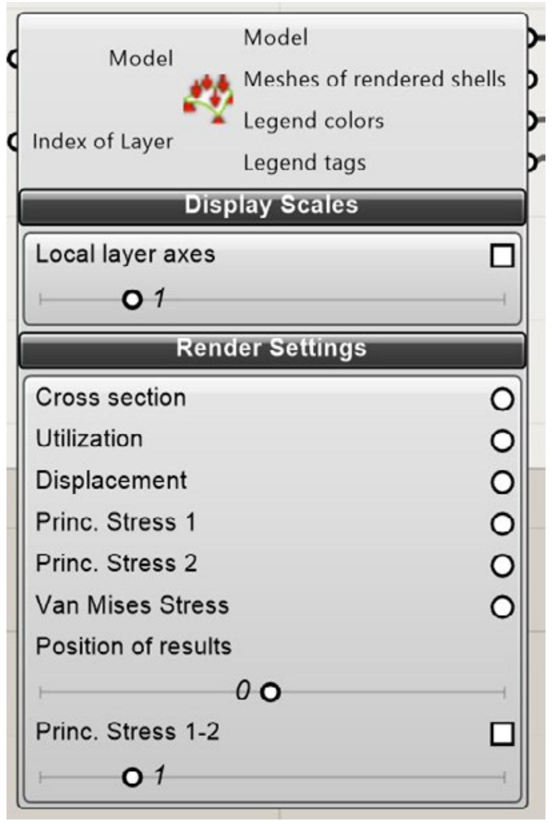
09.4. Adding Loads

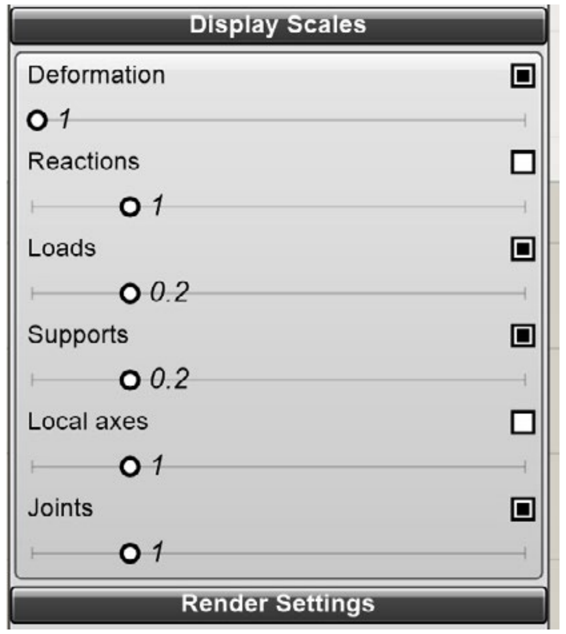


09.5. Material Properties Input

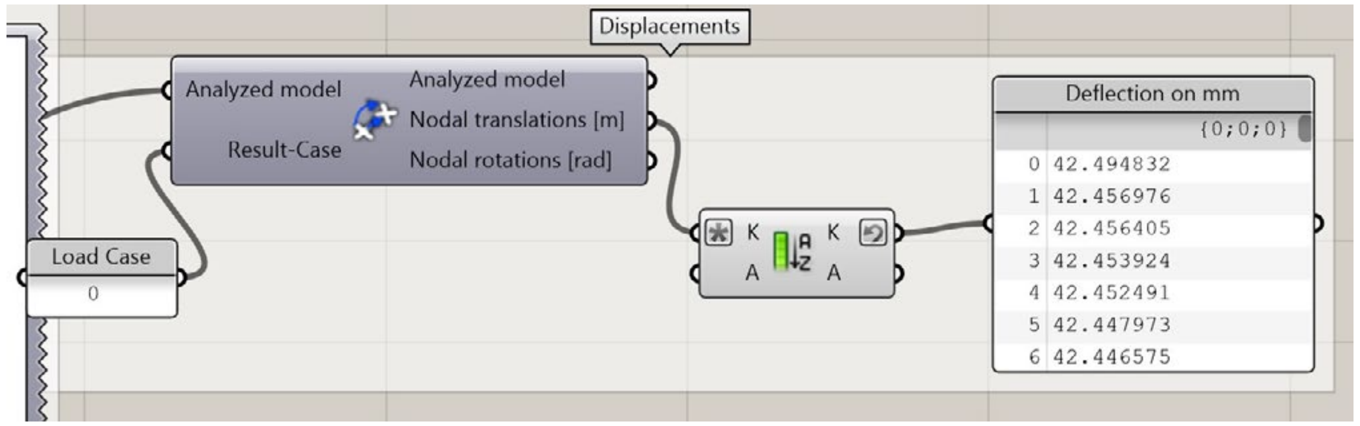


09.6. Solver Visualization





09.7. Deflection on the material due to specified load



Master (Msc) Thesis
Natural Fiber Reinforced Composites & Façade Applications

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