BIOWOUND.

biofiber research laboratory

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on the search for the right material

When trying to find the right sustainable building material, we often come across ideas that sound good in theory but don't quite live up to their promises. The challenge is to make sure that these concepts work well in practice and truly contribute to sustainability. It's important to not just consider theoretical merits but to see how these ideas hold up in real-world situations. This means looking at the environmental, social, and economic aspects to make sure the materials we choose genuinely align with sustainable principles in the building industry.
Current prominent building materials in the construction industry are concrete, steel, brick, and timber, with timber being the only material among the big four capable of sequestering CO2. In considering sustainability within the construction sector, it is important to take into account what nature provides and to what extent we can extract from it. Overexploitation is a threatening and ongoing risk, as excessive utilization may leave limited resources for future generations (TED, 2023).
To understand the term of sustainability, timber, as a recognized sustainable building material, is analysed as an illustrative instance of sustainable utilization. In the case of timber, the main advantage lies in its ability to being a natural carbon sink and renewable.
To grasp these capabilities, it is necessary to establish clear definitions for the terms *carbon neutral* and *renewablep*. When speaking of *carbon neutral* in the building industry the term "relates to measuring, reducing and offsetting carbon energy used by either a building or an organization as a whole" (Carruthers et al., 2013). Its objective is to minimize carbon emissions generated throughout its life cycle. With the decrease of carbon emissions, the material's ability of being renewable implies the potential to naturally replenish and serve multiple generations through reuse (Banton, 2023). But when examining its life cycle of 25 years of growth and 40 years of utilization, coupled with the definition of sustainable harvested timber, which pertains to well managed and continually replenished forests, the already restricted availability of timber and its sustainability diminishes. Excessive logging and high maintenance requirements contribute to the gradual decrease in the sustainability of this building material.

Our capabilities are limited by the provisions of available resources provided by nature. Sustainability of a building material is contingent upon several factors, including the specific location where it is used. It depends on the accessibility of natural, renewable materials with a brief regrowth cycle.
Additionally, sustainability is intertwined with social aspects related to the material, such as its capacity to enhance thermal comfort and maintain a healthy indoor climate within a building. Humans naturally seek comfort within the shelter of buildings, and this desire is most profoundly realised in the familiarity and intimacy of their homes. In these personal spaces, people not only find physical solace but also use them as a canvas to convey their beliefs, hopes, and emotions. Furthermore, a truly sustainable building material should align with the principle of supporting nature rather than depleting or extracting from it. In essence, the sustainability of a building material extends beyond mere environmental considerations; it encompasses the intricate interplay of ecological, social, and location factors in creating a holistic and sustainable solution.

fig.01-01: fossil fuel vs. biobased

Continuing the search for sustainable building materials, which reduce the impact of the construction industry on global warming and align with the principles of nature, the term bio-based materials is associated with those regards.
A biobased material, defined as a substance derived from plant or animal biomass, serves as a raw material in various construction and decoration products, as well as in fixed furniture. This category encompasses grown materials such as timber, hemp, flax, straw, mycelium, and paper, as well as naturally occurring and extracted materials like clay, cement, stones, soil, and similar resources (Francaise, 2012).
Examining their characteristics and performance as building materials, with a specific focus on identifying strengths and weaknesses, is crucial to pinpoint suitable applications for each material.
Concerning straw-built houses for instance, their limited resistance to moisture poses challenges in applications within high-humidity or water-prone areas, particularly those vulnerable to sea-level rise. The increased moisture content presents a heightened risk to the durability of such structures. Examining clay mixtures, the deficiency in suitable thermal properties may result in suboptimal indoor thermal comfort (λ=0.510 [W/mK]). In the realm of building materials and insulation, a preference for lower thermal conductivity is common to improve energy efficiency and maintain comfortable indoor temperatures (e.g. hempcrete λ=0.065 [W/mK]). Conversely, materials with higher thermal conductivity facilitate the easier passage of heat, potentially compromising the thermal comfort of a given space. (Bedlivá et al., 2014).

fig.01-03: principle grown material

fig.01-04: principle extracted material

fig.01-02: compressed biobased materials

fig.01-05: hempcrete wall with lightweight timber frame

Mycelium, when exposed to water for an extended duration, has the potential to lead to the collapse of the material, accompanied by a notable increase in thickness as it absorbs water (Appels et al., 2019). An effective approach of utilizing biobased grown materials could be to combine them with lower environmental impact substances. Lime, for instance, derived from limestone but manufactured at a lower temperature compared to cement, offers a viable option for creating cement-like materials, such as hempcrete (Bedlivá et al., 2014).

Each material, whether biobased or not, possesses its unique set of strengths and weaknesses. Achieving sustainable usage of materials requires a thorough understanding and appropriate utilization of these inherent characteristics. The search for the right material reveals that there isn't a singular perfect solution; instead, it involves identifying and combining various materials effectively.
The notion of a material comprised entirely of 100% sustainable components may appear impractical and idealistic. Instead of pursuing the illusive goal of a wholly sustainable material, the focus should shift towards discovering the most suitable combination of materials. Sustainable material selection involves recognizing that different materials may contribute specific advantages to an application, and by strategically combining them, it is possible to create an environmentally friendly and efficient solution.

research question: how can biofibers, such as hemp and flax, be integrated in a sustainable architectural construction?

how to handle materials ?
what is sustainability in regards to materials?

need of sustainable building materials

When examining the consequences of global warming, the scientific community is aware that the creation and usage of building materials linked to fossil fuels, like concrete and steel, play a large role in the anthropogenic global emissions. Studies show that "the built environment is responsible for almost 40% of global energy-related carbon emissions" (Islam et al., 2021). This includes activities involving the combustion of fossil fuels, land use, waste management, and industrial processes (Matthews, n.d.)(United Nations, n.d.).
As a result of building with a more sustainable and reduced reliance on fossil fuels, the need for sustainable materials is increasing. In order to find an alternative it is imperative to establish a clear definition of the term "sustainable."
In a concise definition, the term "sustainable" can be described as follows: "the ability to maintain or support a process over time" (Mollenkamp, 2023). A sustainable building material offers "specific benefits to the users in terms of low maintenance, energy efficiency, the improvement of occupant health and comfort, the increase of productivity whilst being less harmful to the environment" (Pacheco-Torgalet al., 2014).
Sustainability in materials additionally encompasses the principle of minimizing transportation distances whenever feasible. A related concept in this pursuit is that of *zero km materials*. The *zero km materials* approach promotes the utilization of products that can be obtained from nearby sources, ideally without undergoing extensive industrial processing. Throughout this concept transportation distances are reduced and aligned with the goal of achieving a more sustainable, cost-effective, and environmentally friendly built environment (Souza, 2021).

To enable the investigarion of particular sustainable materials, the scope of this research is defined as follows: This research will focus on the area of Groningen and Hunze River Valley in the Netherlands.
Regarding accessibility of sustainable building materials in and around Groningen and to provide greater detail about the focus on the location, the two biobased materials, hemp and flax, have been selected for in-depth investigation.

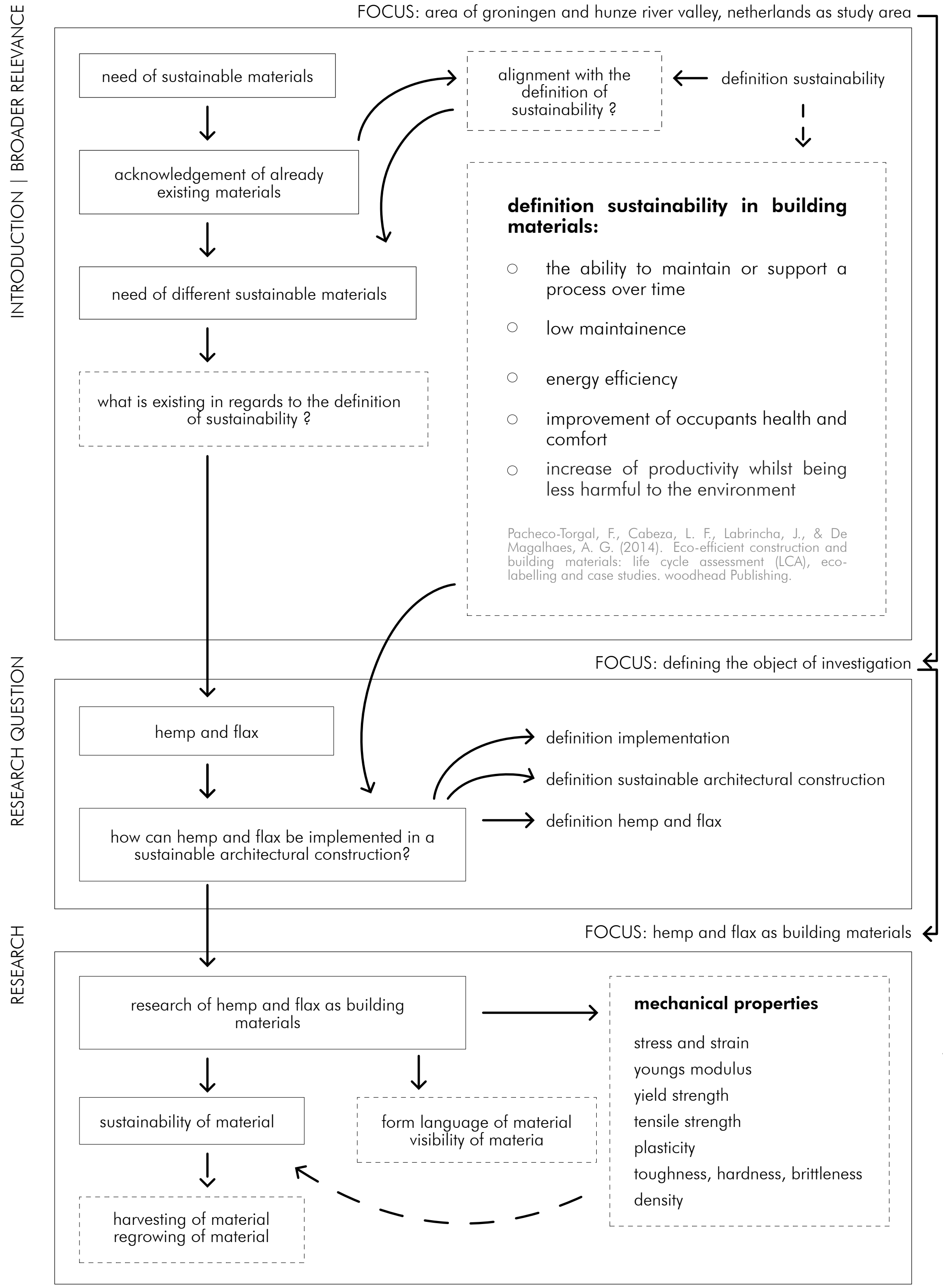

fig.02-01: investigation area mind map

fig.02-02: hempplant

fig.02-03: hempshives

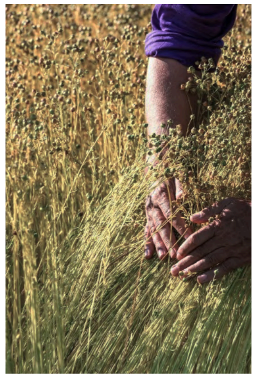

fig.02-04: flaxplant

fig.02-05: flax fiber

When examining Groningen's landscape, it becomes evident that a substantial portion of the region's agricultural focus revolves around the cultivation of aea potatoes and hemp. An examination of the agricultural history of the Netherlands reveals that, from approximately 1700 to 1915, the country operated within a circular economy that heavily relied on industrial crops. These crops played pivotal roles as primary resources in a wide array of industrial processes, with flax and hemp occupying essential positions in this industrial ecosystem (Selten, 2020).
Remarkably, approximately 69% of Dutch hemp cultivation takes place in the Groningen area, which provides a compelling basis for further investigation of its potential as a future building material.
Furthermore, the Netherlands has a profound and longstanding connection with flax. Flax cultivation and the production of linen, a textile crafted from flax fibers, are deeply interwoven with Dutch heritage. Dutch farmers have nurtured flax crops for numerous generations, particularly in regions characterized by favorable climate and soil conditions (Driel et al., 2022).

definition industrial hemp

Industrial hemp, which is an annual crop, is primarily recognized for its fiber-producing capabilities. Throughout its history, these fibers have been predominantly used in the manufacturing of textiles and paper. Additionally, hemp fibers serve various purposes, such as animal bedding, insulation material, fiberboards, and medical applications (Jeliazkov et al., 2019).
The use of hemp fibers as a raw material in construction is not a new concept, as the history of hempcrete in construction dates back at least 1500 years. Hempcrete describes a mixture of hemp shiv, a limebased-binder and water. However, the modern use of hemp in construction did not take hold until 1980 in France, where it was first used to replace deteriorating wattle and daub (Nballiance, 2022).
Despite its long history, hemp has yet to gain independent recognition as a primary building material (Souza, 2020).

definition flax

The flax plant is one of the most ancient plants, often known as the "textile plant." While its primary purpose is the production of linen from its fibers, flax has a range of additional uses. Its flowers can be employed to produce a blue textile dye, and its seeds, particularly linseeds, have substantial importance in the food industry (Jhala et al., 2010). The utilization of flax in the construction industry is a relatively recent development, yet it is already the subject of investigation by various scientists and universities. Their aim is to demonstrate the substantial potential of flax as a future building material (Moore, 2023).

fig.02-06 & 02-07: hempcrete and flax fiber

The main aim of this research is to thoroughly analyze and investigate the potential utilization of hemp and flax as biobased building materials in long-lasting architectural structures. This comprehensive investigation will encompass a multifaceted approach, primarily focusing on the examination of mechanical properties, architectural form language, and the overall sustainability aspects of hemp and flax.
The methodology will involve an extensive literature review to gather in-depth knowledge about the materials, including their mechanical characteristics, ecological benefits, and any relevant advancements or best practices in their application. This theoretical foundation will be further reinforced by conducting case studies of existing buildings that have successfully incorporated hemp and flax as building materials.
Ultimately, this research will strive to answer the following pivotal question:

How can biofibers, such as hemp and flax, be integrated in a sustainable architectural construction?
Within this context, sustainability encompasses the proactive response to impending challenges posed by climate change and the rising sea levels in the Hunze River Valley.

To address these inquiries effectively, a comprehensive analysis and assessment of the contemporary applications of the biobased materials hemp and flax is required. Furthermore, it is imperative to scrutinise and critique the factors that pose obstacles to the implementation of biobased materials in the Hunze River Valley. The process of scrutinizing and critiquing involves a thorough examination of hemp and flax, with the aim of understanding, evaluating, and making informed judgments.
The form language, regarding its freedom of form and movement, and inherent properties are then examined, with a focus on evaluating its advantages and disadvantages. It will shed light on the barriers, flaws, errors, inconsistencies, and challenges that need to be overcome and understood to enhance the widespread use of sustainable and environmentally friendly materials in construction practices.
By comparing the biobased materials with already in the building industry used materials, a more comprehensive understanding of the outcomes will be achieved. The appropriate material for comparison will be selected following the evaluation of the mechanical properties of both hemp and flax. The comparative analysis is expected to yield valuable insights through a multi-faceted approach, including performance evaluation, benchmarking and environmental impact assessment.
The performance evaluation will provide a thorough assessment of biobased materials in comparison to their conventional non-biobased counterparts. By scrutinizing materials with similar characteristics, such as strength, durability, and thermal properties, this evaluation will provide essential insights into the feasibility and appropriateness of biobased materials for diverse applications within architectural construction. This comprehensive assessment is important for a clear understanding of the potential strengths and limitations associated with the use of biobased materials in the field of architecture.

Additionally benchmarks will establish a reference point against which hemp and flax can be measured. Those benchmarks serve as a valuable reference for assessing the performance and effectiveness of biobased materials. It offers a clear perspective on whether these materials can compete with or surpass non-biobased alternatives.


fig.02-08: biobased principle


fig.02-09: various properties


fig.02-10: expression of form

How can biofibers, such as hemp and flax, be integrated in a sustainable architectural construction?

How can this implementation be achieved while addressing forthcoming challenges related to climate change and rising sea levels in the Hunze River Valley?
How can this be utilized to enhance awareness and promote education regarding the benefits and applications of biobased materials?

biobased materials

Biobased materials are as following defined: *a "material resulting from plant or animal biomass that can be used as a raw material in construction and decoration products, fixed furniture and as a construction material in a building." (Francaise, 2012)*

mechanical properties

Every material has its own strengths and weaknesses. The skilful use depends on making effective use of these properties. To maximise the potential of a material, one must utilise its strengths while being aware of its limitations. A thorough analysis of a material's properties includes an examination of their mechanical properties, such as density toughness, hardness, brittleness, plasticity, tensile strength, yield strength, young's modulus, stress and strain.

architectural formlanguage

Every material communicates a unique language through its form and inherent characteristics. The term "form" is defined as "the shape and structure of something distinct from its material" (Merriam-Webster, n.d., Form definition & meaning.). Architect Bjarke Ingels, who emphasizes that design is about "to give form to that which has not taken yet" (Ingels, 2020) underscores the evolution of a material from taking shape to being intentionally given form.
In light of this viewpoint, it becomes evident that a material should be approached and treated with a design philosophy that aligns with its own unique characteristics. These characteristics are best described as a "distinguishing trait, quality, or property" (Merriam-Webster, n.d., Characteristic definition & meaning).
Characteristics refer to the distinguishing features, qualities, or properties that define and describe a particular entity, object, or phenomenon. These attributes help identify and differentiate it from others and play a significant role in understanding its nature or behavior. Characteristics can encompass a wide range of aspects, including physical, chemical, structural, or behavioral traits that provide insight into the unique qualities or attributes of the subject in question.

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how to handle materials ? what is sustainability in regards to materials?

analysis design methods

towards nature inspired design

Sustainable design involves not only utilizing materials from natural and renewable sources but also employing them efficiently. One approach to achieving this efficiency is by studying the forms and structures found in nature.
A comparison between natural and human-made structures reveals a significant contrast in their simplified forms. Nature tends to create rounded structures, optimizing material usage and retaining it only where needed. In contrast, human creations often take the form of boxes, chosen for their efficiency and affordability. However, these box-like structures use approximately 27% more material than necessary.
By deconstructing these box structures and adopting a more nature-inspired design, unnecessary material can be eliminated, resulting in a lighter overall structure (TED, 2023).

It is important to mention that the examination of nature's structures serves as a valuable means to understand the physics of natural structures and explore their potential applications in future architectural designs.

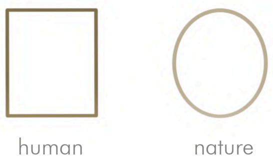

fig.03-01: nature's form

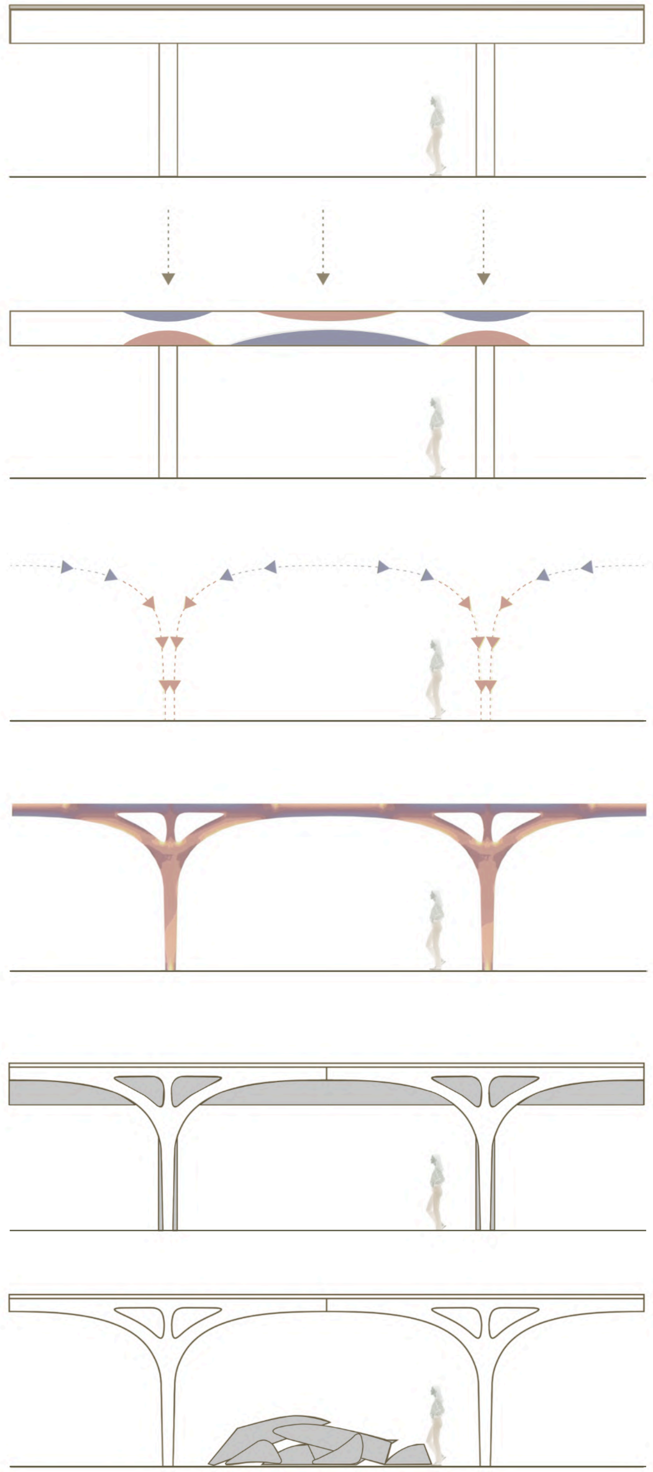

fig.03-02: material efficiency inspired by nature

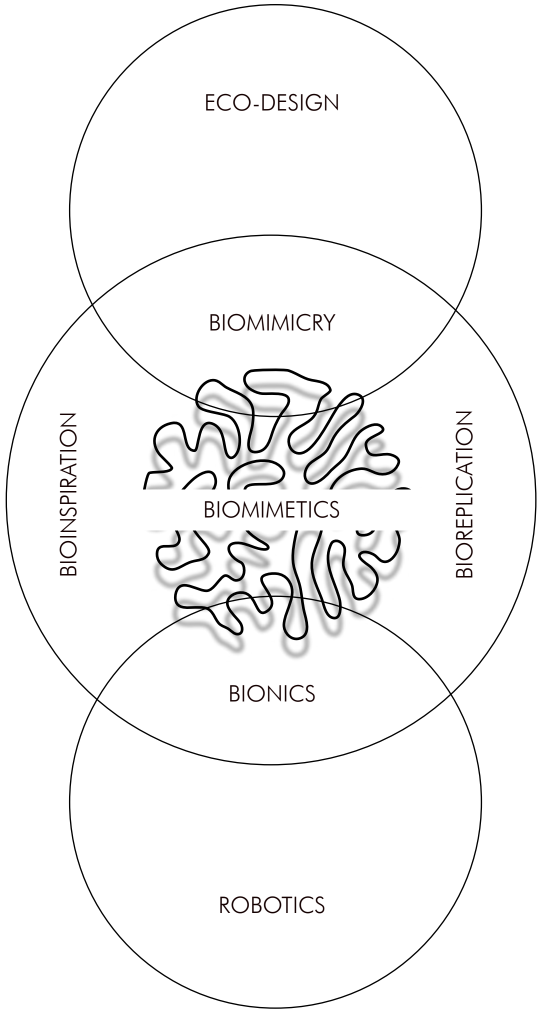

fig.03-03: definition bio-inspired

It’s essential to differentiate between the terms associated with taking inspiration from nature, such as *biomimicry, biomorphism,* and *biomimetrics*. Each term encapsulates distinct aspects of how nature can inform and guide the design process (Pawlyn, 2019).

Biomorphism involves the replication of natural forms, creating designs that resemble elements found in nature. In contrast, *biomimicry* goes beyond mere imitation; it seeks to comprehend the underlying structure and efficiency of natural processes. However, simply duplicating nature's structures does not necessarily result in improved architecture in terms of minimal material usage or efficient structures. The more specific characterisation of *biomimicry* leads to the term *biomimetics*, which refers to the scientific discipline that deals with the structures and principles of nature and ultimately derives technical or architectural solutions from these findings (Pohl et. al., 2015).

Architects such as Buckminster Fuller and Frei Otto tried to understand natural structures and combine them with the aesthetic and functional expressions of buildings to make them appear natural and logical. In the field of architecture, in-depth research is often not possible, which is why a method called "pool research" is used to generate knowledge quickly by reling on pre-research and combining it with different changing solutions (Pohl et. al., 2015).
The integration of biology and technology demands careful consideration when drawing inspiration for architecture and engineering. Emphasizing the significance of abstraction, the goal in investigating nature's structures is not to directly imitate and copy, but rather to comprehend its physics, aesthetics, and processes (Pohl et. al., 2015). Understanding these principles is crucial for enhancing the comprehension of biobased building materials.

In the following, various approaches are examined and brought together in an overview in order to understand the physics of natural materials and to transfer this to an understanding of biobased building materials and their possible implementation in an architectural structure.

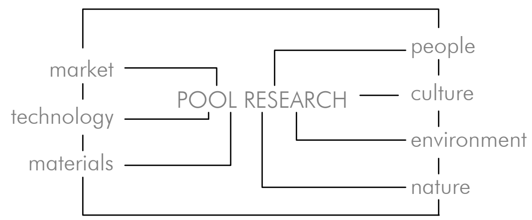

fig.03-04: definition pool research

understanding efficiency

Nature exemplifies an extraordinary efficiency in material utilization, and the objective is to comprehend this efficiency and explore its applicability.
One of the simplest forms employed by nature, and already extensively adopted in the architectural industry, is the hollow tube - a design principle analogous to human bones or a plant's stem. A comparison between a solid squared beam and a hollow tube underscores that the hollow tube, with 20% less material, exhibits equivalent bending and stiffness properties as the solid beam (Pawlyn, 2019).
This concept aligns with the biological principle known as the "*axiom of uniform stress*" (Pawlyn, 2019). In biological structures, materials are distributed evenly in regions of stress concentration. This stands in contrast to, for instance, a steel beam, where the beam's dimensions are determined by the highest load condition at a specific point.
Understanding nature's stress distribution involves observing stress lines of a human's bone, which demonstrate how asymmetrical forces are resolved. Comparing X-rays with the bone's stress lines reveals a precise alignment between the density of bone filaments and stress concentration. A notable inference is that high stress correlates with increased material proliferation (Pawlyn, 2019).

Architecture maintains a close correlation with physics. The aim is not to perceive physics as an opponent but rather as a tool that can offer various new design methods and forms.

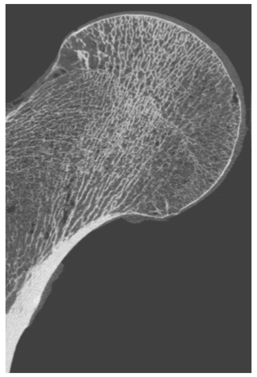

fig.03-05: x ray of a bone

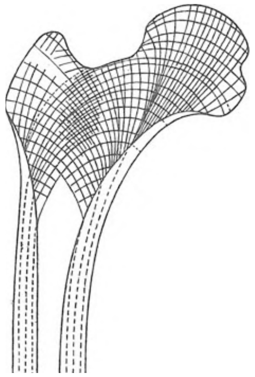

fig.03-06: stress lines of a bone

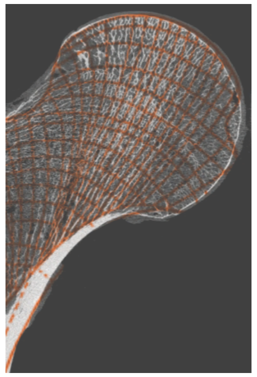

fig.03-07: bones filament density

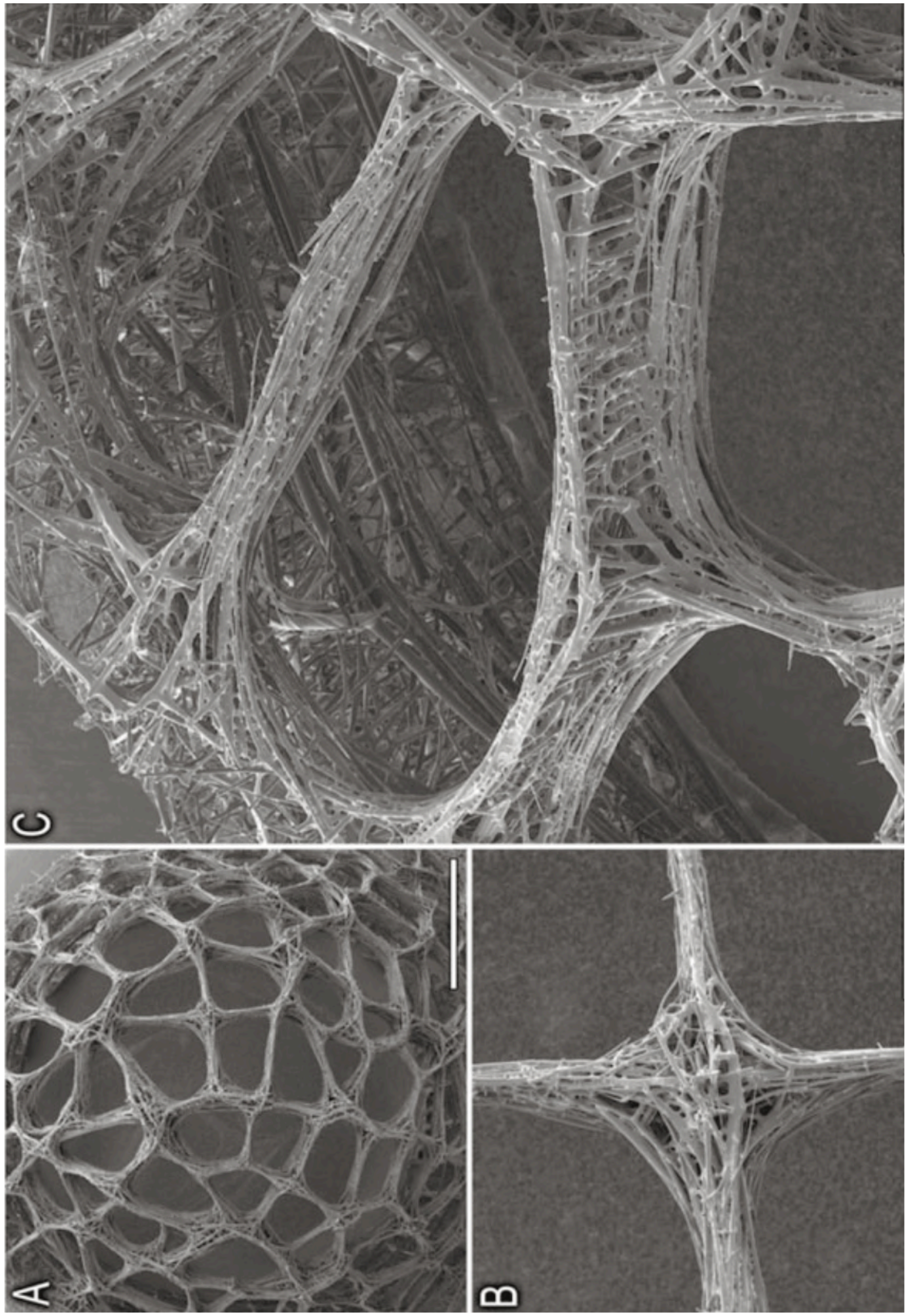

fig.03-08: inner wall of the cylindrical skeletal lattice

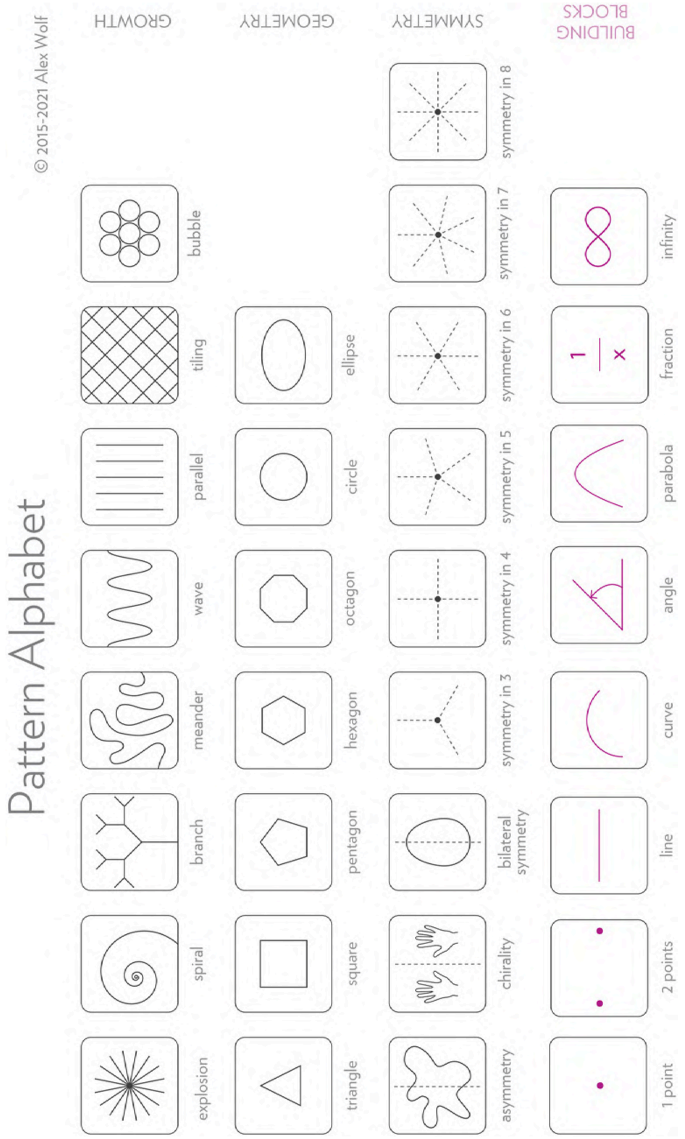

fig.03-09: nature's pattern alphabet

understanding patterns

One method to understand nature's forms is analysing its various patterns. Nature provides many different patterns, which are repeating, standardized and predictable structures. Those recurring patterns are essential for plants and animals and represent years of optimization through natures evolution and therefore efficiency. Alex Wolf made an version of the alphabet of natures patterns trying to understand the visual tools and form-language of nature. Those patterns are divided in growth patterns, geometric patterns, symmetric patterns and different modifiers also called building blocks. The categorisation enables a more systematic understanding of the complex web of nature. Growth patterns illustrate the dynamic processes inherent in the development of living organisms, geometric patterns reveal the underlying mathematical precision, symmetrical patterns show balance and harmony, while modifiers or building blocks represent the various elements that contribute to the overall complexity of natural structures (Wolf et al., 2022).

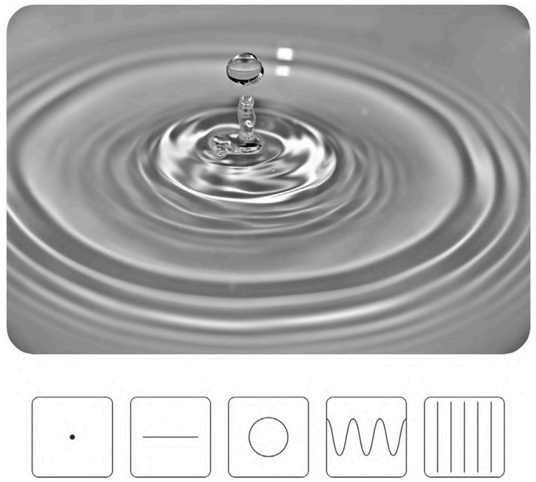

fig.03-10: patternABC to describe the phenomena of water droplet

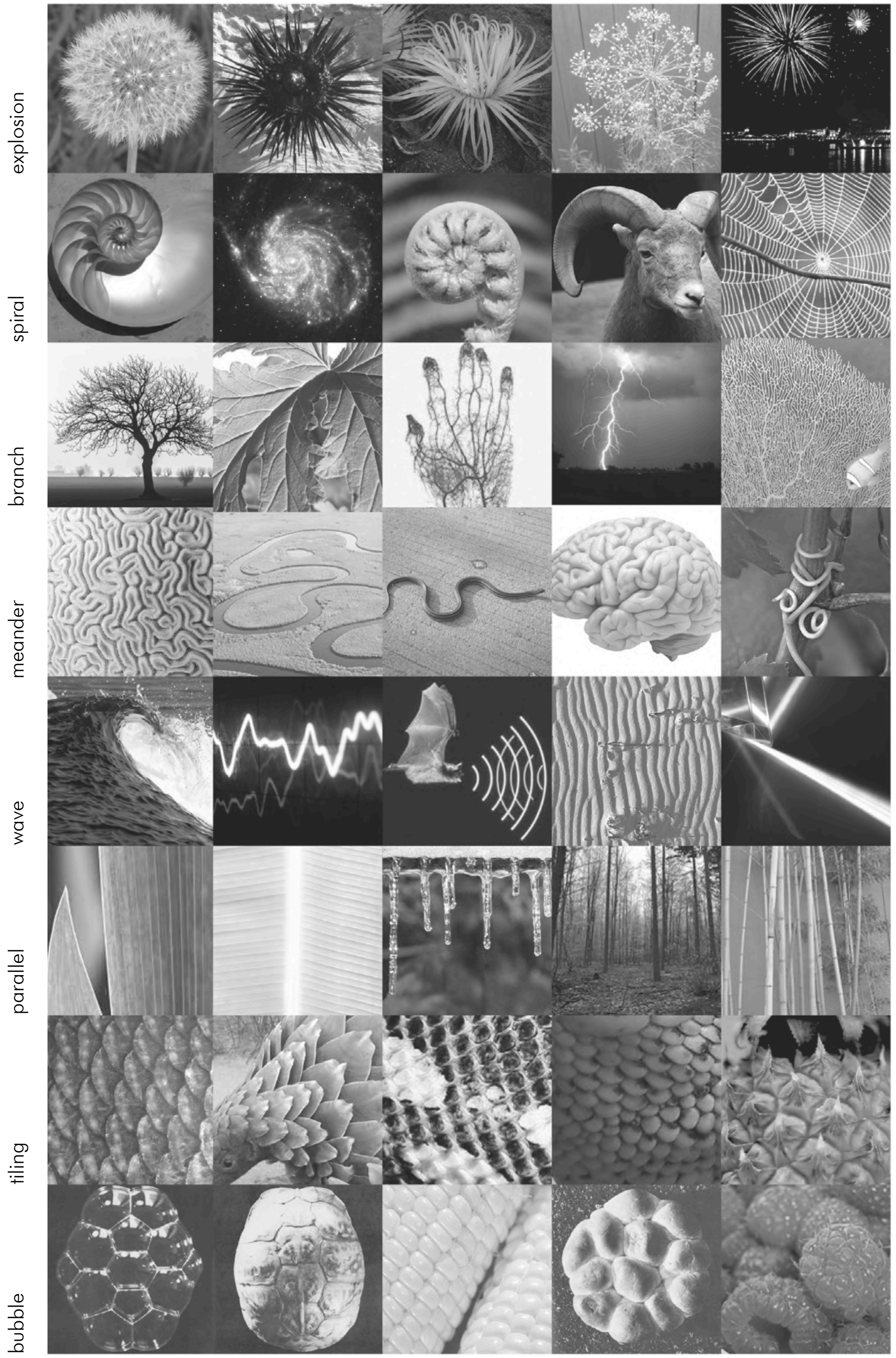

fig.03-11: growth pattern examples in nature

fig.03-11: growth pattern examples in nature

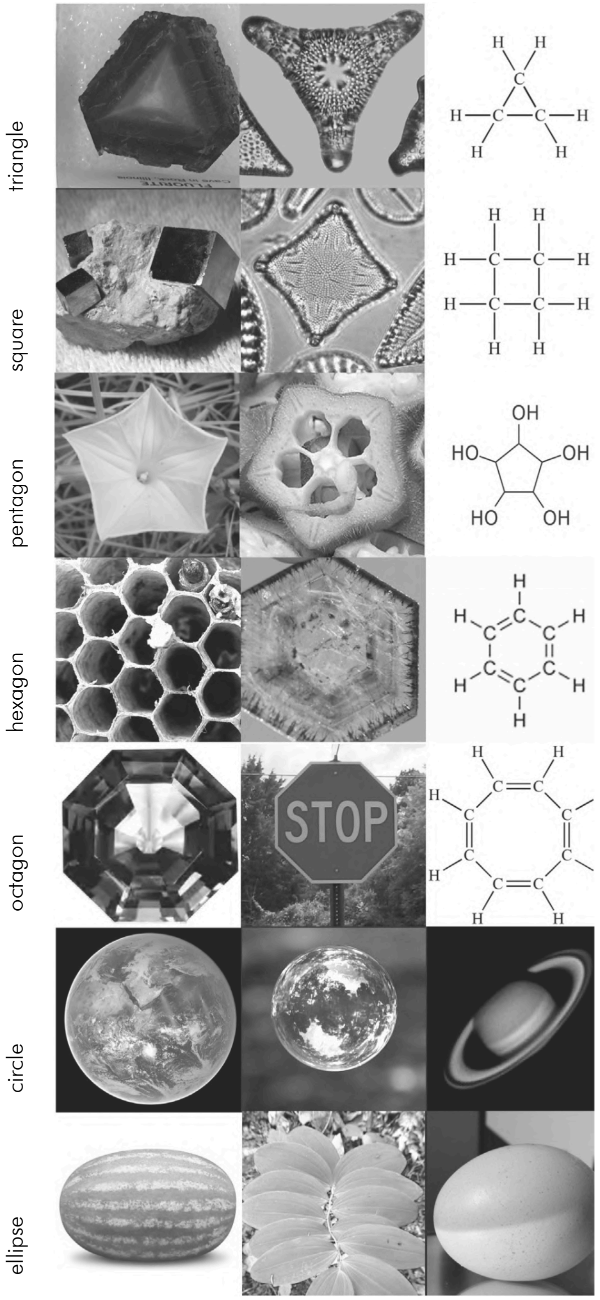

fig.03-12: growth pattern examples in nature

fig.03-12: growth pattern examples in nature

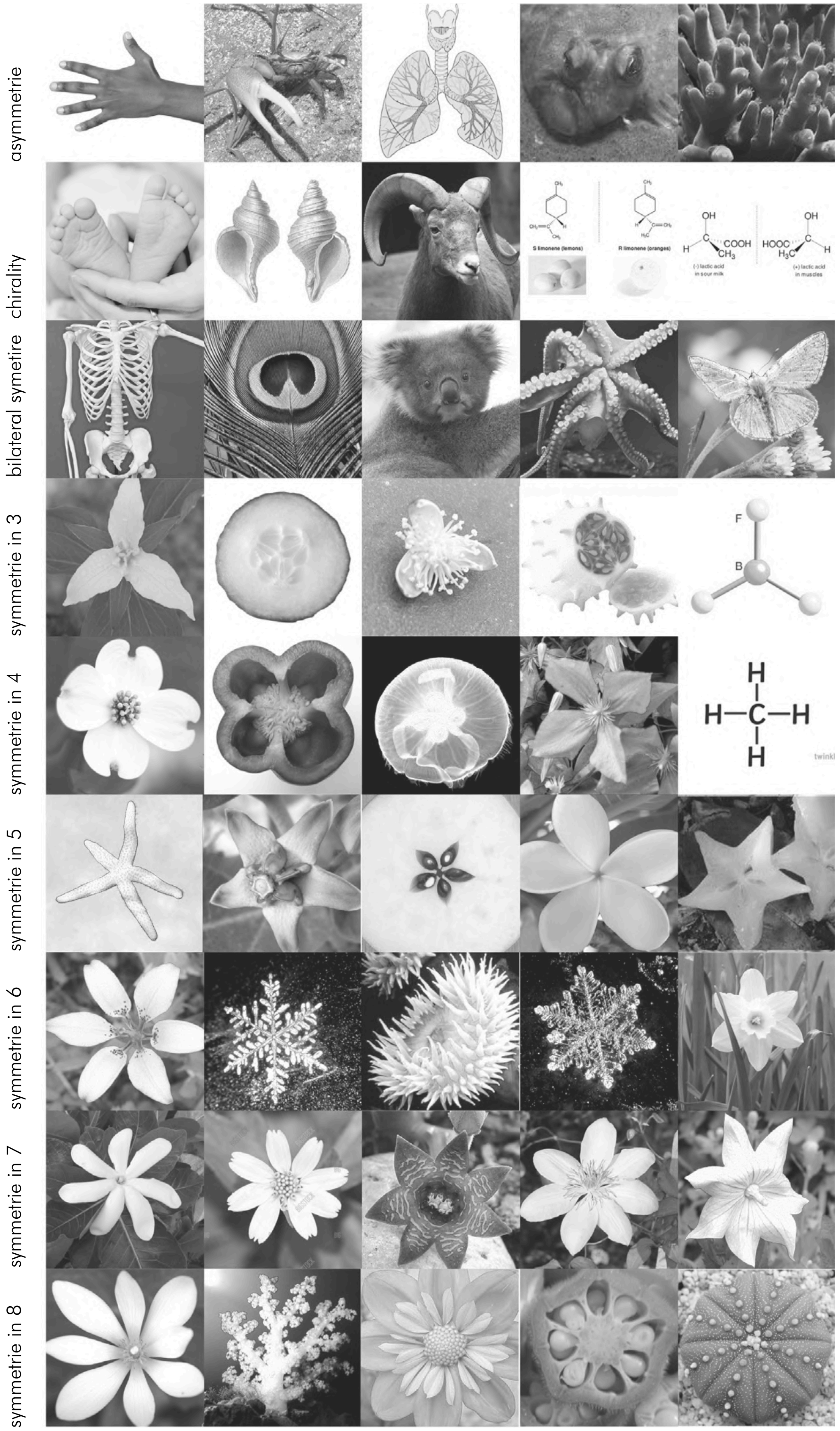

fig.03-13: growth pattern examples in nature

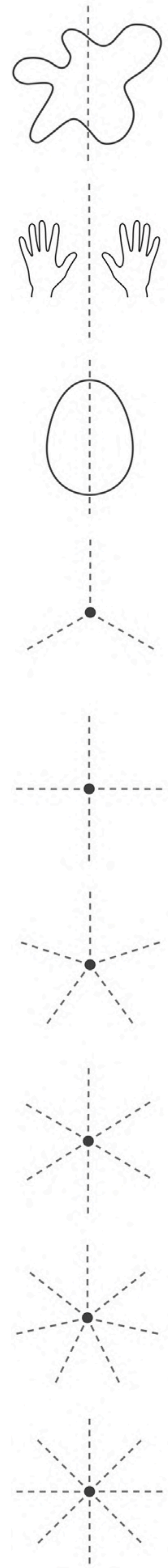

fig.03-13: growth pattern examples in nature

finding form

Through the exploration of natural patterns and both its technological and physical properties, biometric research has the potential to form a design strategy. Architect Frei Otto, tried to comprehend nature-inspired design and attempted to understand its methods of shaping form and function.
In his book "Gestalt finden," Otto discusses the building industry's shift towards minimalism and nature-inspired design, emphasizing the evolution of lightweight constructions. This evolution brings about a fresh perspective on nature from both aesthetic and ethical standpoints. Otto considers natural constructions a pivotal focus for the future, stressing the significance of comprehending growth and general natural processes. He posits that an object's form results from diverse processes, and what he terms the *opposite way* signifies acknowledging nature not solely through understanding it but also through grasping its technical evolution (Otto et al., 1995).
Frei Otto employed experimental methodologies as a key aspect of his form-finding approach. By constructing models and conducting tests, he developed his unique design methodology. Subsequently, in his publications, he documented numerous constructions that had undergone thorough examination through experimental processes.

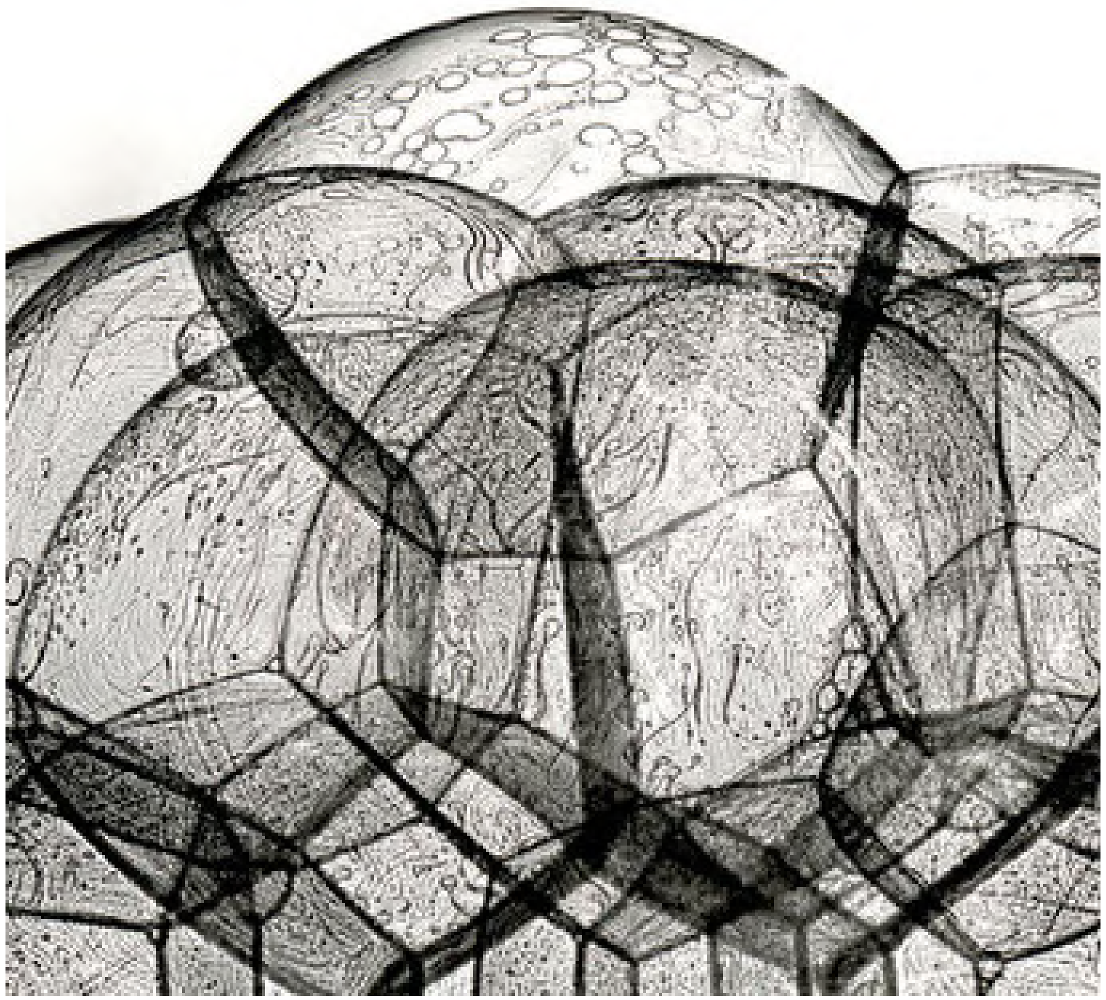

fig.03-14: frei otto's soapskin model

fig.03-15: frei otto "tanzbrunnen" 1957, cologne germany

tent construction

Tent construction, an old architectural method, involving the use of stretched membranes as its fundamental building components. Experiment through soapskin model (Otto et al., 1995).

fig.03-16: soapskin model of "tanzbrunnen"

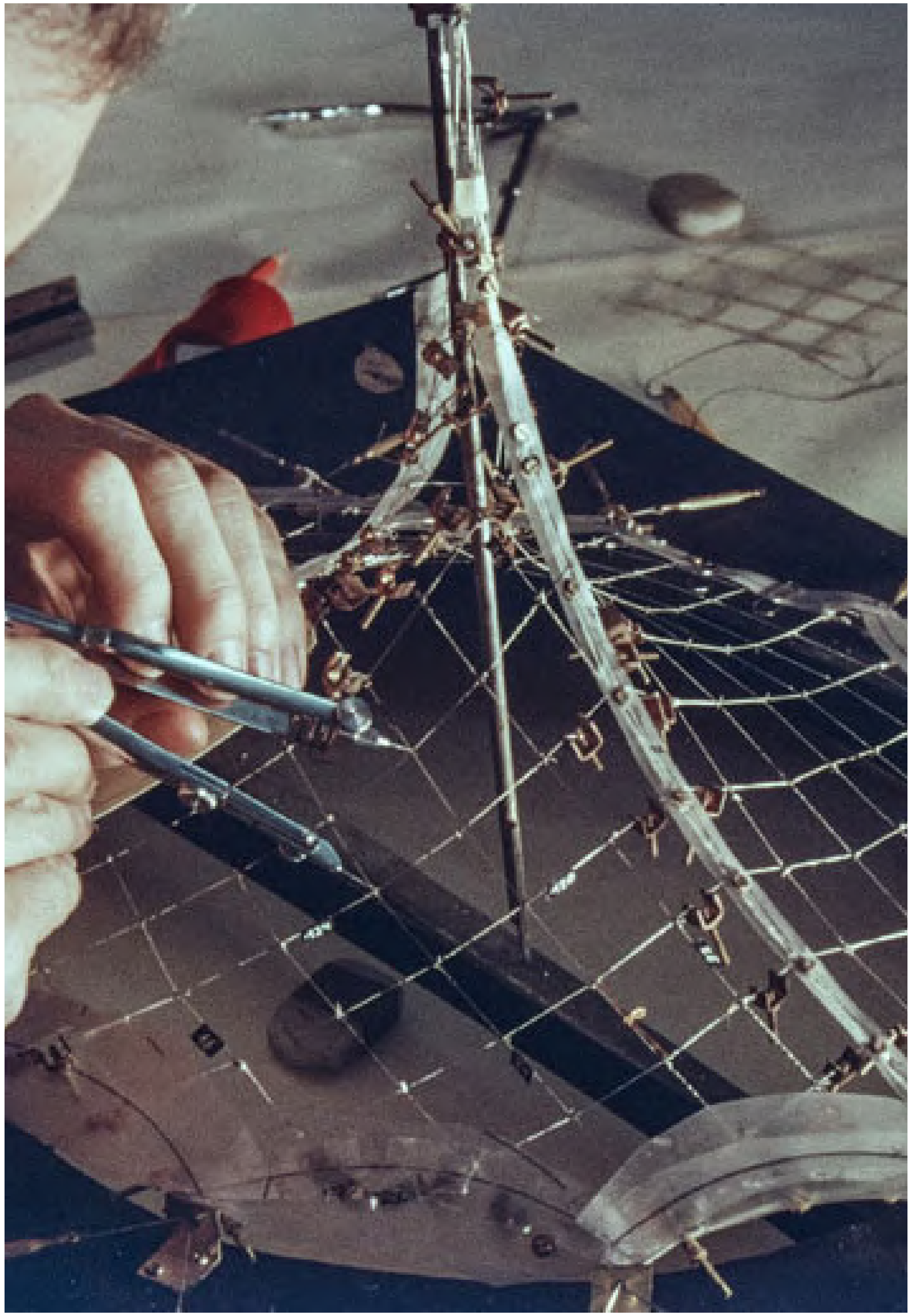

fig.03-17: wire net model to show the deformation when subject to weight impact

fig.03-18: frei otto "deutscher pavillion" 1967, montral canada

net construction

Net constructions, akin to tent structures but featuring uniform meshes, enable wider spans. Experiment through a double-exposed wire model showing deformation of the mesh under load (Otto et al., 1995).

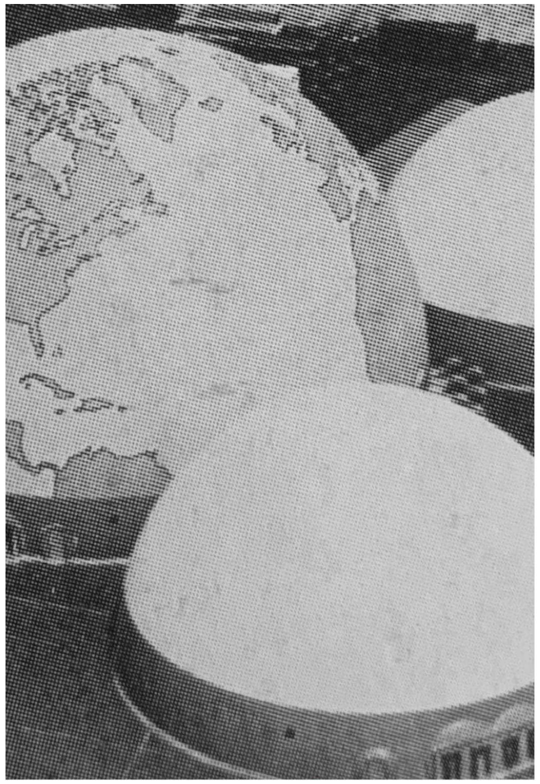

fig.03-19: frei otto "penta-dome" 1958

pneumatic construction

Pneumatic construction, pre-stressed membranes supported by air pressure, using air as a load-bearing element. Experiments through gypsum models with constrictions or soapskin models with or without constrictions (Otto et al., 1995).

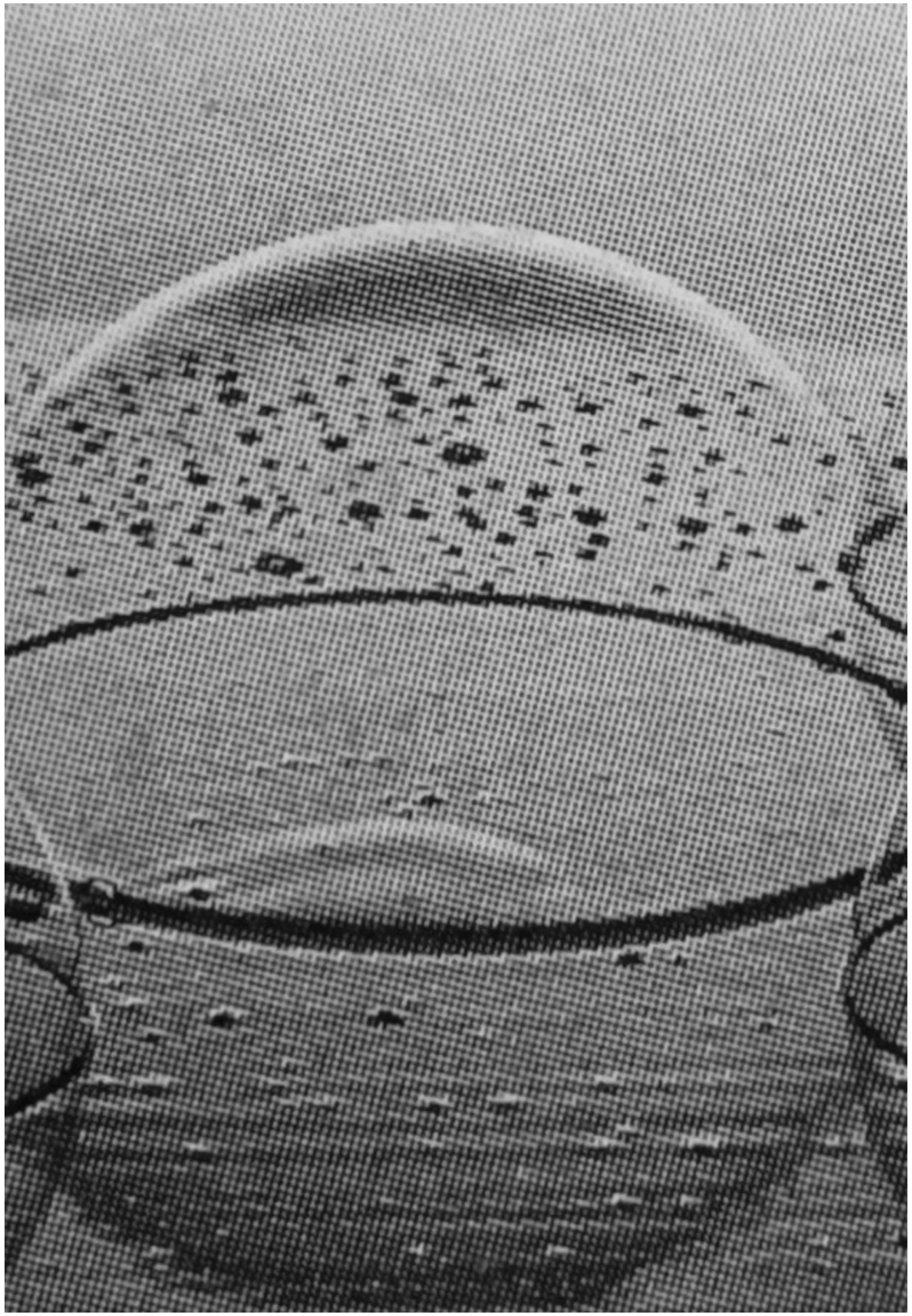

fig.03-20: soapskin model, surface tension minimum systems

fig.03-21: suspended tensile structures model

fig.03-22: frei otto "voliere in munich zoo", 1980, munich germany

suspended structures

Suspended structures, typically curved on one side, rely solely on their own weight for stabilization in experiments without pre-tensioning. Such structures may incorporate a rigid roof system for reinforcement or employ bracing mechanisms (Otto et al., 1995).

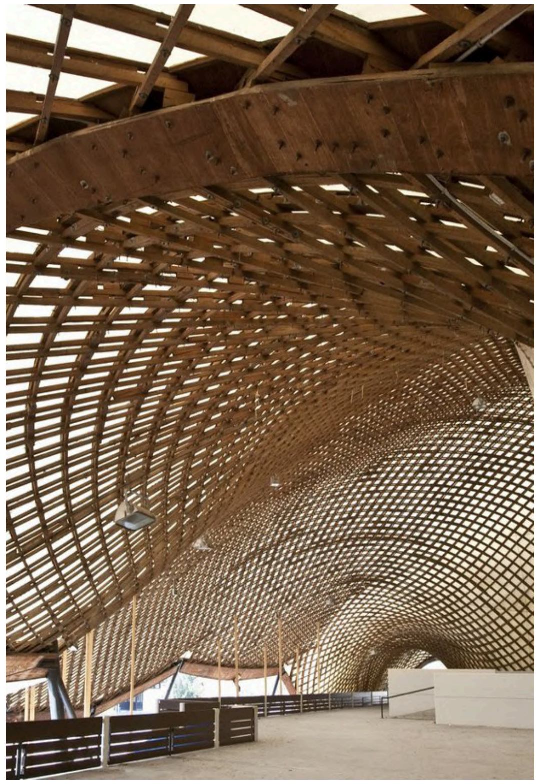

fig.03-23: frei otto "mulothalle mannheim", 1975, mannheim germany

arches, vaults, and shell constructions

In experiments, the configuration of arches, vaults, and shell constructions is influenced by the rotation of the chain line, aiming to identify the optimal support line. Initially governed by tensile forces in the suspended structure, a 180-degree rotation transforms it into arch-like shapes, enabling the absorption of compressive forces (Otto et al., 1995).

fig.03-24:inversed hanging model

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hemp fibers and its composites

Hemp offers countless applications in various industries and serves as a versatile resource. Its use ranges from the manufacture of ropes, nets and textiles to its subsequent role in paper production, highlighting the plant's remarkable versatility (Demir & Doğan, 2020).
Furthermore, the use of hemp as a raw material in construction is not a new concept, as the history of hemp in construction dates back at least 1500 years. However, the modern use of hemp in construction did not take hold until 1980 in France, where it was first used to replace deteriorating wattle and daub (Nballiance, 2022).
When the hemp plant, its seeds and flowers are being processed, a waste product from the hemp plant is being leftover. The so called hemp shiv can then be further used in order to create a lightweight building material. While mixing hemp shiv with water and a limebased binder, the so called hempcrete can be cast in place, moulded in a brick or in any form or spray applied. Once fully dried, this lightweight and durable material exhibits high crack resistance, making it suitable for use in earthquake-prone areas (Yadav et al., 2022).
The hemp plant is a rapidly growing annual plant (120 days of growth cycle) that typically develops only a few branches. It ranges in height from 1.5 meters to 4 meters, featuring fibers that can reach lengths of up to 2.1 meters. The plant possesses a thin stem with a diameter spanning from 4mm to 20 mm. Historically, the inner woody stem, from which shives are derived, was barely utilized and considered a byproduct of harvesting seeds, flowers, and fibers.

fig.04-01: cannabis sativa l. - industrial hemp

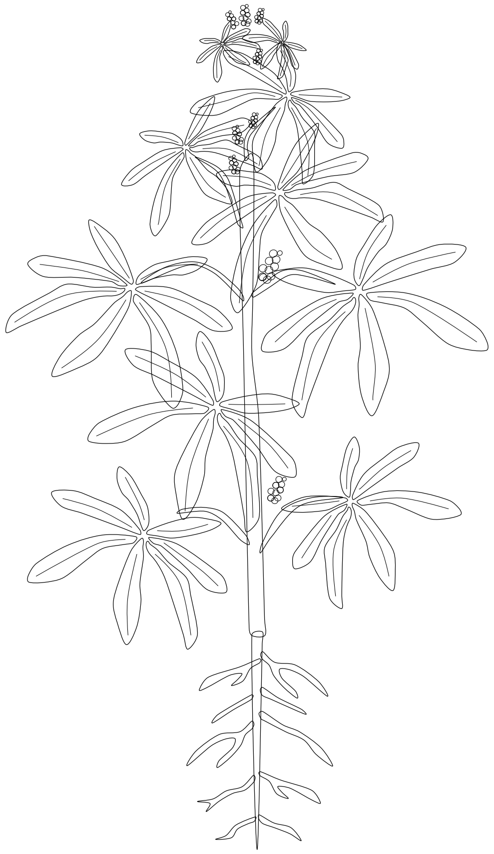


fig.04-02: cannabis sativa l.

<u>flowers</u>
- *animal bedding*
- *mulch/compost*
- *medicine/recreation*

<u>seeds</u>
- oil
  - *cooking oil*
  - *dietary supplement*
  - *body care products*
  - *fuel*
  - *paint*
- seed cake
  - *flour*
  - *beer*
  - *animal feed*
- hemp nut
  - *milk / dairy*
  - *bakery*
  - *granola*
  - *protein powder*

<u>stalk</u>
- fiber
  - *textiles*
  - *insulation*
  - *rope*
- hurds
  - *paper*
  - *organic compost*
  - *animal bedding*
  - *fiber board*

<u>roots</u>
- *medicine*
- *organic compost*

Nowadays and following the processing of the hemp plant, shives still remain as a byproduct. To repurpose them for hempcrete, the plant undergoes a process where fibers are extracted from the stem, dust is being removed and the plant is broken down into small pieces. The production of hemp shives involves a procedure akin to the harvesting of flax fibers, encompassing processes such as decortication, retting, and scutching *(see chapter on processing flax fibers)*(Cableveyconvey, 2023).
To ensure optimal suitability for hempcrete, the hemp shiv must be dry and free of dust. The shives' length should fall between 10 and 25 mm, as this length dictates the matrix of the composite, subsequently influencing its mechanical, thermal properties, and overall performance.
The removal of dust and fibers is crucial in preventing these components from absorbing water during the mixing process with the binder. This precaution ensures that the right amount of water combines with the binder, preventing any compromise in its effectiveness.
Similar caution should be exercised in proper storage; maintaining hemp in a dry environment and away from water safeguards its properties for future applications.
Once hemp shives are cast as hempcrete, the lime binder effectively provides protection against insects, fire, and dampness (Stanwix et al., 2014).

fig.04-03: cleaned hemp shives

mechanical properties

Hempcrete has a high porosity on a macroscopic level, which gives it a natural flexibility characterised by elasticity, flexural strength, lightness, absorption capacity and commendable thermal and acoustic properties. The hemp plant and its shives are robust, wood-like cellulose materials that can withstand repeated cycles of absorption and desorption over an almost unlimited period of time, as long as constant immersion in water or a constant supply of water is avoided. This inherent property is known as *hygroscopicity* and refers to the capillarity of the cell walls, which attract, store and release moisture as required.
In its dry state, hempcrete has an inherent resistance to fire. Depending on the positioning of the load-bearing element within the hempcrete, it acts as an additional natural fire barrier. In initial tests, a hempcrete wall remained intact for around 1 hour and 40 minutes (Stanwix et al., 2014). Although this time span is shorter than the 4-hour fire resistance of concrete, in combination with a load-bearing timber construction, hempcrete extends the 60 minute fire resistance of timber to 2 hours and 40 minutes (Fire, n.d.). The centralised arrangement of hempcrete proves to be particularly effective in increasing fire resistance (Stanwix et al., 2014).

Despite its limited compressive strength, which makes it unsuitable as a sole building material, hempcrete has excellent flexural strength. This property allows it to flex under certain loads without cracking, making it a viable option for construction in earthquake-prone areas and for seismic structures. When incorporated into a frame structure, hempcrete increases racking strength and performs similar functions to bracing (Stanwix et al., 2014).
A major benefit and advantage of hemp in construction is its exceptional insulating properties. Depending on its thickness, hempcrete alone can eliminate the need for additional insulation (see fig.04-09). In addition, the addition of a lime-hemp plaster improves the overall insulating ability of the construction. To summarise, hempcrete's diverse and beneficial properties make it a sustainable, flexible and fire-resistant building material that offers significant potential for various construction applications (Stanwix et al., 2014).

MATERIAL	youngs modulus (MPa)	compressive strength (MPa)
steel	210 000	350 - 1 000
concrete	20 000	12 - 80
brick	10 000 - 25 000	25 - 60
wood	230 - 20 000	4 - 34
lime hempcrete	24	0.4

MATERIAL	density (kg/m2)	thermal conductivity (W/M°C)
steel	7 500 - 8 500	52.00
concrete	20 000	1.50
brick	1 300 - 1 700	0.27 - 0.96
wood	350 - 900	0.12 - 0.30
lime hempcrete	445	0.17

WALL THICKNESS (mm)	250	300	350	400
u-value hempcrete (W/m2K)	0.23	0.20	0.17	0.15
u-value concrete (W/m2K)	1.70	1.40	1.20	1.00
u-value timber (W/m2K)	0.60	0.50	0.40	0.35
u-value rockwool (W/m2K)	0.22	0.18	0.15	0.13

fig.04-04: mechanical properties hempcrete

current application methods

Hempcrete presents a versatile construction material suitable for the use of walls, floors, or roofs. Its application is adaptable, offering three primary methods: *cast-in-place, spray application, or prefabrication into blocks or panels* (Stanwix et al., 2014).

cast-in-situ

The *cast-in-situ* placing method is a technique that involves on-site application of hempcrete, offering flexibility in the construction process. This versatile method allows for pouring, hand placement, or spraying of the hempcrete mixture to create a structural and insulating layer. Typically, this application surrounds a load-bearing lightweight structure, often consisting of a timber frame.
The placement of a hempcrete wall can vary based on the specific needs of the project. It can be centralized, forming a core within the construction, or applied internally or externally to the load-bearing structure. The decision on placement depends on various factors, including project requirements and design considerations.
In situations where heavy objects are anticipated to be attached to the internal wall, a logical choice is to keep the timber frame visible on the interior. This not only ensures the structural integrity needed for load-bearing purposes but also serves aesthetic and design functions. By strategically placing the load-bearing structure, the design can showcase the natural and appealing characteristics of the timber frame while providing a functional and eco-friendly hempcrete layer for insulation and structural support (Stanwix et al., 2014).

fig.04-05: cast in situ

fig.04-06: spray applied

fig.04-07: prefabricated bricks

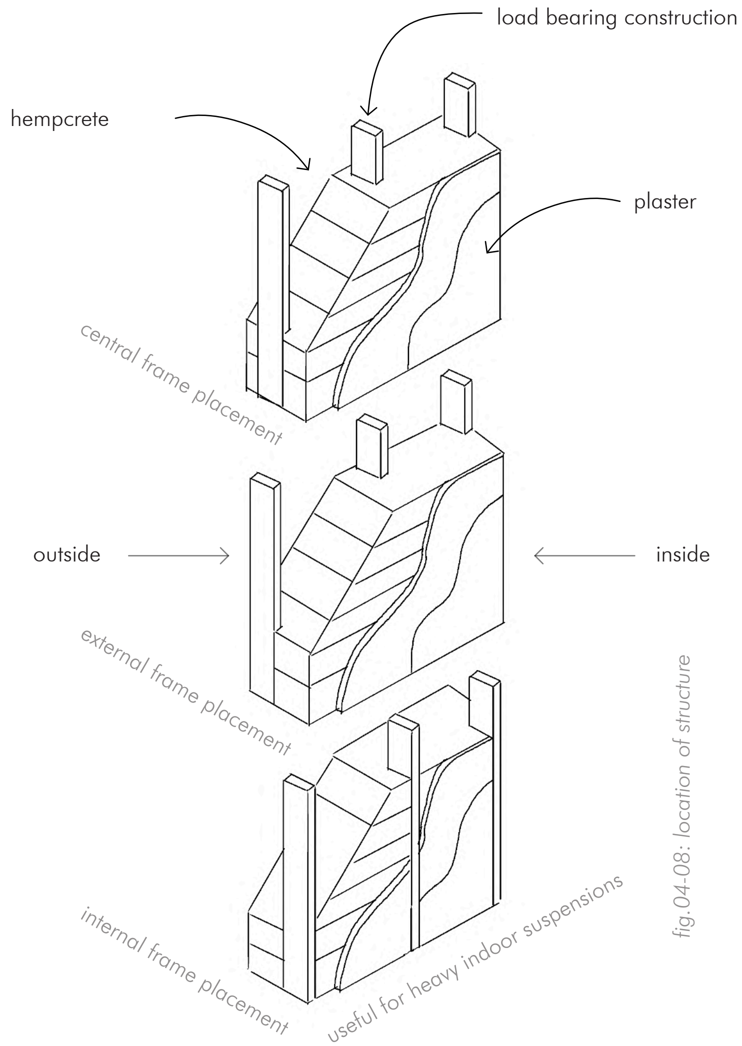


fig.04-08: location of structure

fig.04-09: Flat House / Practice Architecture + Material Cultures

spray applied

The technique of hempcrete *spraying* requires the use of specialised equipment to quickly coat surfaces. This method proves to be extremely efficient when it comes to coating large areas quickly and is particularly valuable for complicated or difficult to access spaces. The key feature is the even application, which is vital for even insulation and the thermal performance.
When *spraying* hempcrete, it is important to use finer hemp chips than when applying it *in situ*. This finer grit contributes to a more even application. This method does not require a second formwork panel, but an open and accessible frame for optimum application. This feature makes *spray application* an attractive option for projects where speed, precision and accessibility are needed (Stanwix et al., 2014).

prefabricated

A third application method for hempcrete involves *prefabrication in blocks or panels*. In the *prefabrication* process, hempcrete blocks or panels are created off-site and following transported to and assembled at the construction site. This approach rationalises the construction process, enhancing efficiency and precision. In addition, prefabricated hempcrete components can shorten the construction time and offer the possibility of quality control in a controlled production environment.
Prefabrication off-site eliminates uncertainties regarding material behavior and the drying process. However, attention must be given to the potential creation of thermal bridges, which can occur through the stacking of blocks. In order to avoid this the hempcrete blocks are stacked with a thin layer of mortar in between. Hempcrete blocks can be easily cut by hand and adjusted to fit specific requirements.
Despite its advantages, there are drawbacks to the prefabrication method. One limitation is the higher mixing ratio of binder to hemp shives, and the material being more vulnerable during manufacturing, storage, and transportation due to its extended dried period before implementing. Additionally, prefabricated bricks still require a secondary load-bearing structure for support (Stanwix et al., 2014).

thermal regulation

lightweight - one eight of concrete

sound regulation

fireproof

mold proof and vermit resistance

can endure periodic wetting

short growth cycle (120 days)

insects resistance

waste product

odor proof

local production (Europe)

CO2 sequestering

pros

lack of experts

can not be used under water

need of lime-based binder

more expensive than concrete

needs additional construction

cons

research question: how can biofibers, such as hemp and flax, be integrated in a sustainable architectural construction?

how to handle materials ? what is sustainability in regards to materials?

analysis design methods

flax fibers and its composites

Various natural fibers are available for use as reinforcement or fillers to support other materials structure. Typically, fibers are composed of elongated cells with relatively thick cell walls, imparting stiffness and strength. In many fibre plants, these cells are bound together to form long, slender fibres, the length of which depends on the size of the plant.
The fibers of the flax plant are primarily found in the stems of the flax bast plant, which can grow up to a length of 90 cm. Notably, this plant has a short growth cycle, with planting typically occurring in March and harvest readiness achieved by July of the same year. During growth, the flax plant already binds CO2, which distinguishes the biofibre from other non-renewable fibres such as glass fibres (Garikapati et al. 2018). Currently, there are two cultivated types of flax plants: flax fiber plants and flax seed plants.Fibre flax is bred to produce thin, robust fibres, while seed plants are optimised for maximum seed production and consist of multiple stems.
In terms of processing, flax undergoes various transformations. It can be converted into *filaments/spun into yarn*, formed into a *web*, or *chopped* into smaller pieces. This versatility in processing enables the adaptation of flax fibers to a wide array of manufacturing techniques, accommodating different industry needs. Whether in *filament* or *chopped* form, the inherent properties of flax fibers position them as a promising material for various applications, potentially serving as a sustainable and eco-friendly alternative to conventional materials (Yan, 2014).

fig.05-01: flax field

fig.05-02: linum usitatissimum

<u>seeds</u>

- *linseeds*
- oil
  - *cooking oil*
  - *biodiesel*
  - *liposome*
  - *medical use (omega 3,6,9)*
  - *paint*
  - *varnishes*

<u>stalk</u>

- *animal bedding*
- fiber
  - *textiles*
  - *insulation*
  - *rope*
  - *paper*
  - *yarn*

<u>flower</u>

- *blue fabric dye*

fig.05-03: retting

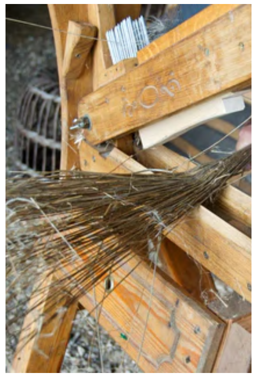


fig.05-04: scutching

fig.05-05: hackling / combing

flax fiber processing

The process of obtaining and enhancing flax fibers begins with retting, an initial phase where flax stems undergo a carefully controlled soaking. This soaking effectively breaks down pectins and other binding agents, facilitating the separation of fibers from the stem. This natural retting process is achievable through methods such as water retting, dew retting, or chemical retting. After retting, the fibers move on to the scutching stage, where the woody portion of the stem is mechanically removed. This step plays a critical role in further isolating and refining the flax fibers, ensuring the elimination of impurities and unwanted materials.
The final stage in this process is combing or hackling, during which the flax fibers undergo alignment and parallelization.
This combing step significantly improves the overall quality and consistency of the fibers, rendering them well-suited for a diverse range of applications, including textile production.
In essence, the extraction and refinement of flax fibers involve a progressive series of steps, each contributing to the enhancement of fiber quality and utility. The thoroughness of this process ensures that the resulting fibers possess the desired characteristics for their intended applications (Gomez-Campos et al., 2021).

The flax fiber, characterized by its multilayer composition consisting of concentric walls, exhibits similarities with glass fibers. This recognition prompts the consideration of utilizing flax fibers as potential substitutes for glass fibers in upcoming projects. Unlike glass fiber composites, which may face challenges in recycling due to their inherent characteristics, flax fiber composites offer a more environmentally friendly solution through thermal recycling (Bos, 2004).

mechanical properties

Examination of the cross-section of a fibre bundle shows the presence of 10 to 40 individual fibres. At the macroscopic level, a flax stem showcases a structured arrangement from its outer layer to the inner part, encompassing bark, phloem, xylem, and a central void. Each layer is comprised of microfibrils of cellulose, with cellulose acting as the primary organic component. While cellulose imparts strength to the fiber, it also makes it vulnerable to moisture absorption (Yan, 2014).

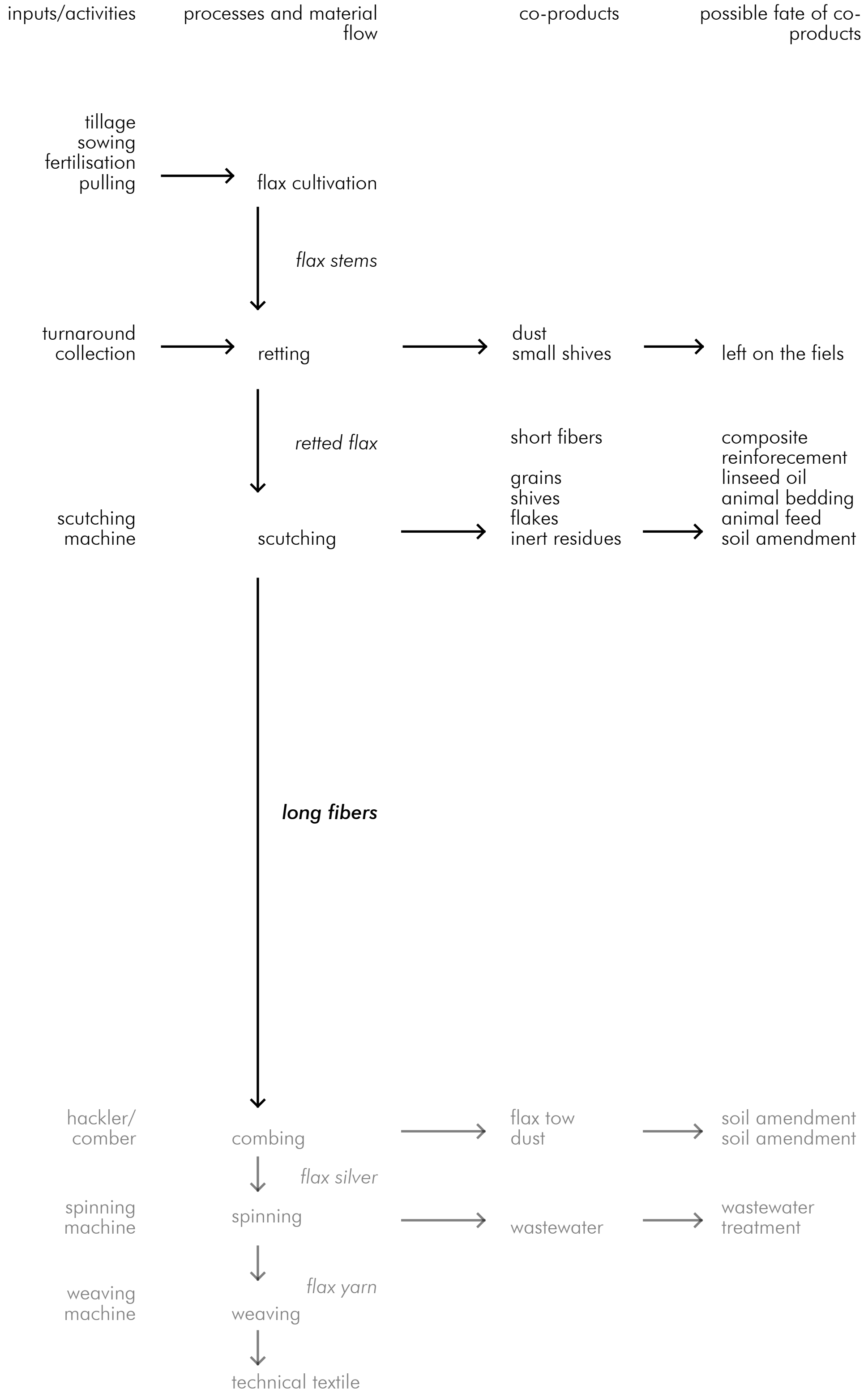


fig.05-06: flax processing

FIBERS	relative density (G/cm3)	elongation at failure (%)
carbon	1.7-1.9	0.4-1.9
glass	2.5-2.7	1.8-5.4
flax	1.4-1.5	1.2-3.3
hemp	1.4-1.5	1.0-3.5
jute	1.3-1.49	1.0-1.8
oilbased resin	1.1	7.0-10.0
biobased resin	1.09	5.0

FIBERS	elastic modulus E (Gpa)	tensile strength (Mpa)
carbon	230-250	2000-3000
glass	70-76	2000-3500
flax	27.6-103	343-2000
hemp	23.5-90	270-900
jute	26-43	320-800
oilbased resin	3-6	60-125
biobased resin	3.2	67.5

FIBERS	energy intensity (MJ/kg)	global warming potential (GWP)
carbon	183-459	16.38
glass	13-51	2.95
flax	6.5-9.55	0.437
hemp	8.9	0.531
jute	9.6	0.57
oilbased resin	76-80	4.7-8.1
biobased resin	49	4.08

fig.05-07: mechanical properties flax fibers

current application methods

Flax fibers, possessing mechanical properties akin to glass fibers, offer a versatile array of applications, including use as *filaments, spun yarn, webs, or in the form of chopped or milled* particles.

chopping and milling

Exploring flax fibers in the form of *milled or chopped particles*, with a specific emphasis on shives, unveils intriguing possibilities within architectural contexts when combined with other composite materials. This combination leads to the creation of a composite material known as flax-lime-concrete, drawing parallels with prior studies on a similar material called hempcrete (*see chapter on hempcrete application methods*). Similar to hempcrete, flax-lime concrete can be moulded into blocks, cast in place, or spray applied (Garikapati et al. 2020).


fig.05-08: compressed flax block

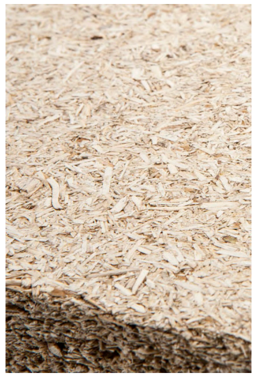


fig.05-09: flaxshiv texture

Constructed from recycled flax shives and strengthened with added jute fabric, the flax-lime concrete block exhibits mechanical behaviours akin to hempcrete.
According to the findings of Krishna Priyanka Garikapati and Pedram Sadeghian, which included a test series of compressive and tensile behaviour, the overall mechanical performance of flax-lime-concrete improved with an increase in the number of jute reinforcements.
This enhancement resulted in greater bending capacity and improved energy absorption. The compressive behavior was tested in a cylindrical form under pure axial compression, and the stress-strain curve demonstrated behavior akin to that of foam materials, displaying similarities in linear elasticity, yielding, and densification.
The test results indicated a yielding strength of approximately 200kPa and a tensile rupture strength of 64kPa (Garikapati et al. 2020).

Primarily, flax shives, and fiber shives in a broader sense, stand out as insulation materials, showcasing impressive thermal and acoustic insulation properties. Apart from their insulating capabilities, these shives can serve effectively as filler materials in lightweight constructions. It's crucial to emphasize that, similar to hempcrete, flax-lime-concrete isn't engineered to bear structural loads; rather, it excels as a versatile filler material with various applications in construction contexts (Garikapati et al. 2020).

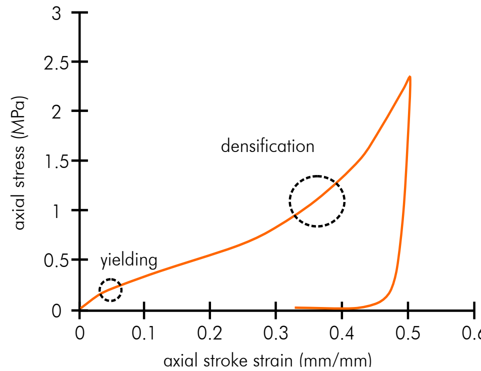


fig.05-10: stress strain curve flax-lime-concrete

STRESS STRAIN average value	initial stiffness (MPa)	yielding strength (MPa)	densification stress (kPa)	strain hardening stiffness (kPa)
flax-lime-concrete	3	0.2	500	7000
reinforced-concrete	24000-40000	2-5	-	-

fig.05-11: average result stress strain test

webs

In the realm of architectural applications involving textiles, a wide variety of possibilities unfolds. The primary determinant of a textile's form in architecture is its tension. Textiles are primarily used in lightweight constructions as geotextiles, shading elements, reinforcements or components of façade constructions (FIBRO_SKIN, 2022).
Among the diverse range of materials, textiles with a biological origin are gaining attention, with flax, commonly known as the textile plant, taking center stage due to its historical association with linen production. This makes flax fabric not only suitable for clothing but also for integration into architectural designs. Flax fabric in construction manifests in three main types: the *prepreg tape*, a resin-infused textile where the fabric undergoes resin infusion during manufacturing; the *unidirectional fabric*, a dry fabric; and the *woven fabric* (Gomez-Campos et al., 2021).
Focusing on the *prepreg fabric*, when combined with resin, it transforms into a rigid panel that can be further employed as façade paneling. The fabrication process involves coating one or multiple fabric strips with resin and subsequently hardening them. The material's flexibility before the resin stage allows for the creation of panels in various forms. In a subsequent phase, individual dried fabrics can be merged with other dried panels using the same resin-coating method, resulting in the formation of larger textile panel surfaces. This multi-stage process offers flexibility in design and construction.

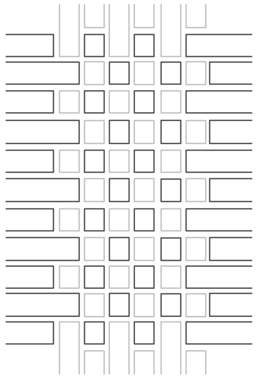


fig.05-12: weaving texture plain 1/1

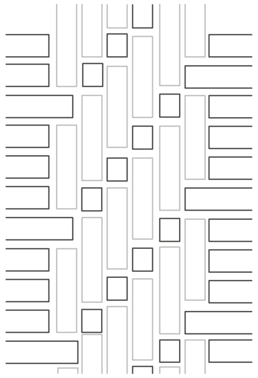


fig.05-13: weaving texture twill 1/3

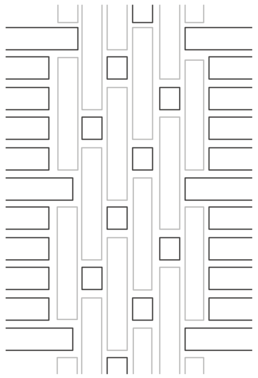


fig.05-14: weaving texture satin 1/4

When it comes to textiles in architecture, different design principles can be achieved, while keeping in mind that the main form of textiles in architecture result from tensioned membranes. Focusing on the construction of the textiles, textiles are per definition "types of cloth or fabric, especially ones that have been woven" (TEXTILE, 2024). When weaving and double weaving in this construction, individual strands are first produced, which are then joined and interlaced to form a uniform fabric. Furthermore, textiles can be produced through *warp knitting, or non-woven techniques* (Moor et al., 2014).

Warp knitting is "a knitting process in which the yarn is knitted vertically in a flat form", (WARP KNITTING, 2024), whereas *nonwovens* are "web structures bonded together by entangling fiber or filaments (and by perforating films) mechanically, thermally, or chemically. They are flat, porous sheets that are made directly from separate fibers or from molten plastic or plastic film" (INDA, 2022). These textiles can be stretched between an additional structure with the support of spacer threads. In the realm of textile design, paying attention to proportion is crucial, particularly in surface design. When working with proportions, decisions regarding patterns, size, and repetition play a significant role. Elements such as the relationship between figure and ground, the choice between abstract and figurative forms, color selection with considerations for contrast or harmony, and decisions regarding a matte or brilliant finish, as well as a structured or plain surface, are key considerations in textile design (Moor et al., 2014).


fig.05-15: flax textiles/webs

project: fibro skin

The production of this bio-composite panel starts with the utilization of flax fibers and laminated bio-resin. The initial phase involves laying down the first textile made from flax fibers onto a specialized mold, carefully conforming to the desired shape.
Subsequently, a the next step involves the infusion of resin into the fabric. This is achieved by creating a vacuum environment, facilitated by a pump. The vacuum not only aids in removing air from the fabric but also allows the resin to thoroughly penetrate and adhere to the flax fibers. Once in place, the laid fabric undergoes a drying process to ensure its stability and shape conservation. This meticulous process ensures a strong and homogeneous bond between the fibers and the resin, contributing to the overall structural integrity of the bio-composite panel.
The layering process follows, wherein additional fabric is incrementally applied over the existing layers on the mold. Simultaneously, resin is systematically applied to each layer as it is laid down. This iterative approach contributes to the gradual buildup of the composite material, optimizing its strength and cohesion.
To finalize the manufacturing process and ensure a smooth surface finish, the assembled layers are covered with a peel ply. The peel ply serves the dual purpose of providing a clean surface finish and facilitating the removal of excess resin. Once covered, the entire assembly is placed into a vacuum bed.
This step enhances consolidation, aiding in the removal of any remaining air pockets and further promoting the adhesion of the fabric and resin layers.
In summary, the production of this bio-composite panel involves a meticulous sequence of steps, from the initial laying of flax fiber textiles and resin infusion under vacuum to the layer-by-layer application of fabric and resin, concluding with the covering and vacuum bed treatment for a well-consolidated, high-quality composite material (FIBRO_SKIN, 2022).

fig.05-16: flax fiber sheet

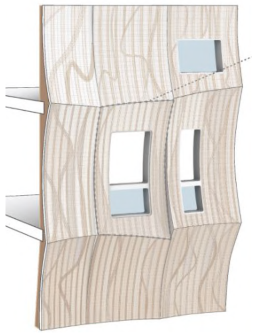


fig.05-17: facade approach

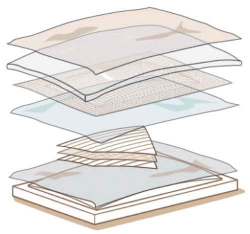


fig.05-18: molding method

fig.05-19: processing and work flow

fig.05-20: cfw winding structure

fig.05-21: winding methods

spun yarn - filament winding

The utilization of fibers in a yarn-like manner shares foundational similarities with weaving principles, but it transcends conventional methods by not confining itself to the creation of two-dimensional fabrics. Instead, it extends the interwoven yarns into a third dimension through a technique known as filament winding.
Filament winding mirrors a fabrication method used for fiber-reinforced polymers (FRP), including fibers like glass, carbon, or flax. In this process, a minimal framework is employed, and the fiber yarn is systematically wound around it. The wrapping or winding is predefined and executed by a robotic arm. Tension, fiber direction, and placement sequence are intricately linked to the desired final form. The stiffness and load-bearing capacity directly correlate with the chosen fabrication methodology. The desired form is meticulously studied through study models and computational generation.
Filament winding proves to be a swift and cost-effective fabrication method, allowing for the rapid production of serial elements. These elements can be substantial components that are easily combined with others. The technique offers a high fiber-to-volume ratio, resulting in exceptional stiffness and strength.
In architecture, three distinct methods of filament winding are prevalent: winding on a mandrel/mold, coreless filament winding, and spatial filament winding. When winding on a mandrel/mold, the mandrel/mold ensures the still-uncured filament remains in place. However, this method requires a time-consuming preparation of the mandrel and limits the achievable forms to shapes like pipes or vessels.
To overcome these limitations, coreless filament winding presents an alternative method without a mold. With coreless filament winding, the production of double-curved surfaces becomes feasible, expanding the range of architectural possibilities (La Magna et al., 2014).
Coreless filament winding represents an innovative approach, integrating computational co-design principles that seamlessly intertwine the challenges of design, manufacturing, and evaluation in a synergistic relationship.

"CFW is an additive manufacturing process in which an impregnated fiber bundle is spanned between point-like anchors for generating thermoset fiber-reinforced composite structures." (Mindermann, 2022)

In the realm of CFW methodology, there is a departure from conventional design paradigms. The emphasis shifts towards prioritizing geometric form, considering materials not merely as elements but as integral means for implementation. The combination of computational processes facilitates a dynamic interface between the digital and physical realms, where material behavior and capabilities take center stage in the generative process of form (Bodea et al., 2021)(Zechmeister et al., 2023).

Diverse forms generated through CFW can serve varied functions, such as mimicking the tension attributes found in textiles or functioning as structural slabs. The tensile strength of these forms is intricately tied to the clamping length, underlining the critical role of this parameter in

achieving desired mechanical properties. In coreless filament winding, the need for an inner core is eliminated, distinguishing it from traditional filament winding methods. Instead of relying on a central core, the fiber rovings are strategically positioned between the longitudinal edges of the winding tool for trusses or wound around pins. This departure from a central core offers certain advantages in terms of flexibility and adaptability in the manufacturing process.
To achieve a multiaxial winding configuration, where fibers are oriented in various directions, a diverse collection of robotic arms are integrated into the manufacturing process. These robotic arms play a pivotal role in precisely guiding and placing the fiber rovings, allowing for a controlled and intricate arrangement of the reinforcing material.
This integration enhances the overall versatility of the filament winding process, enabling the production of composite structures with tailored mechanical properties to meet specific design requirements (Bodea et al., 2021)(Zechmeister et al., 2023).

In practice, CFW involves the utilization of a robotic arm that spans through a resin-dragged fiber yarn across different anchor points. The resultant interspanned form is then subjected to a drying process and subsequently impregnated with an additional layer of resin to enhance the structural stiffness of the element. This methodical and iterative approach exemplifies the fusion of cutting-edge technology, material science, and design thinking in the realm of coreless filament winding (Bodea et al., 2021)(Zechmeister et al., 2023).

Spatial winding, in contrast, takes the coreless filament winding principle a step further by integrating the winding process around both anchors and the fiber itself. In this method, the fiber acts as a novel anchor and formwork for additional fiber filaments. Despite utilizing a simple frame, spatial winding has the capability to generate high geometries within its framework (Duque Estrada et al., 2020).

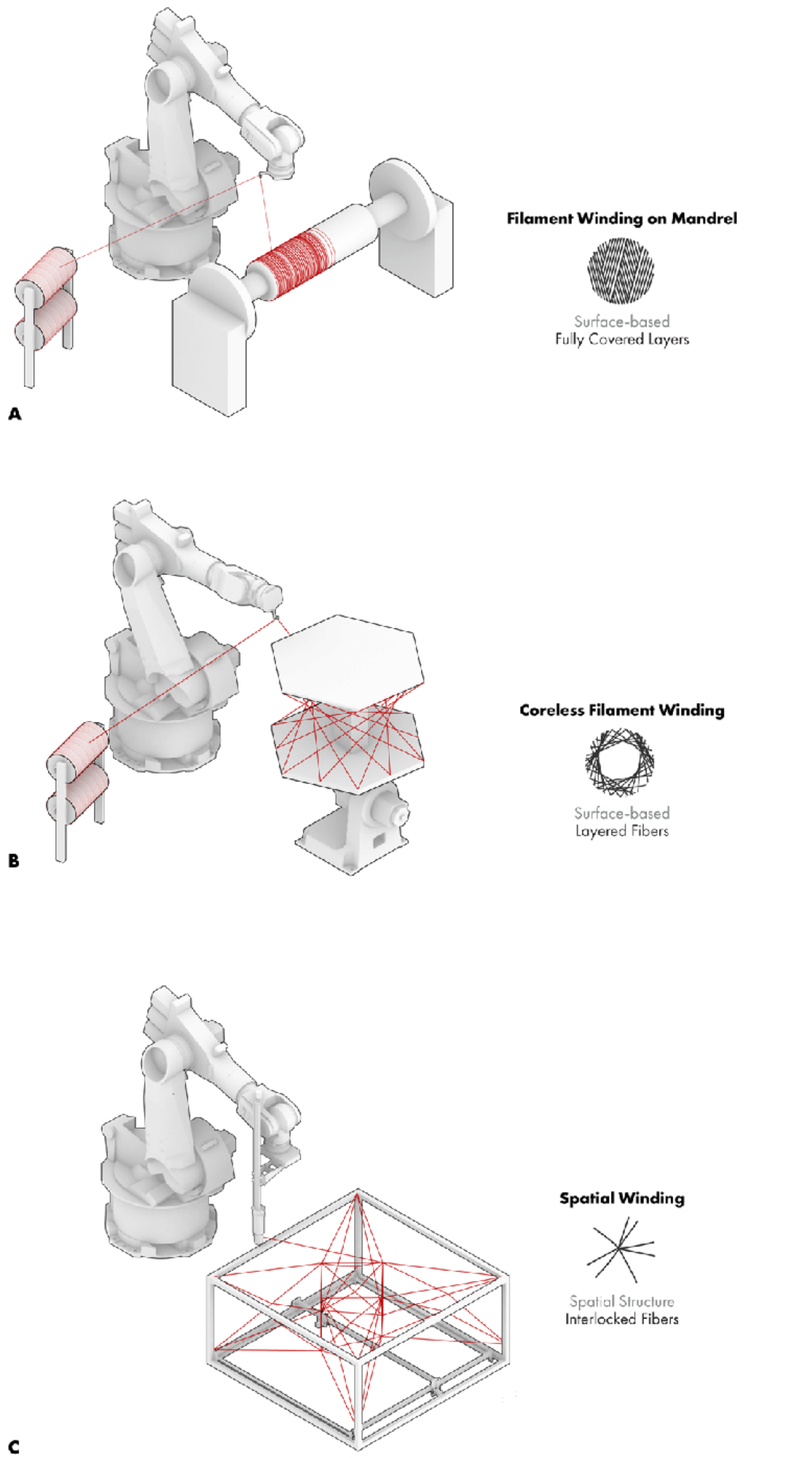


fig.05-22: winding methods manufacturing

project: livMatS pavilion

The pavilion is composed of 15 innovative coreless structural load-bearing elements, crafted through a cutting-edge process known as coreless filament winding (CFW). This method, employed in additive manufacturing, holds the advantage of generating minimal waste while enabling the use of the same modular winding frame for multiple elements. The CFW technique involves winding filament from one anchor point to another, creating a seamless and efficient production process.
The individual columns of the pavilion exhibit a tube-like geometry, which has been subdivided into distinct front and back surfaces. The design approach incorporates various fiber layup typologies, each meticulously identified through prior research focusing on carbon fiber formations. The selection of fiber layup typologies is critical, particularly in considering the structural requirements of the pavilion.
In the research findings of the Institute for Computational Design and Construction, it is established that truss-like fiber formations are not suitable for high compression areas due to their lower stiffness. Conversely, lattice formations are more appropriate for withstanding such forces. This strategic choice aims to optimize the structural integrity and performance of the load-bearing elements.
To address concerns related to sagging, a solution involving the implementation of sisal yarn during the winding process was adopted. This addition serves to enhance the overall stability of the structure, mitigating the risk of deformation and ensuring a robust load-bearing capacity.
Following the completion of the winding process, an additional step involves the impregnation of the structure. This post-processing measure further fortifies the integrity of the coreless filament-wound elements, providing enhanced durability and resilience to external forces (LIVMATS Pavilion, Institute for Computational Design and Construction, University of Stuttgart, n.d.) (Pérez et al., 2022).

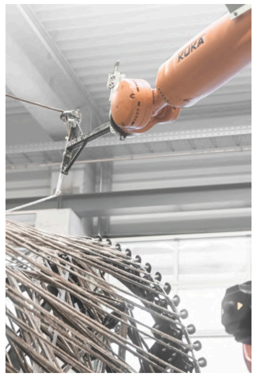


fig.05-23: cfw- robotic arm

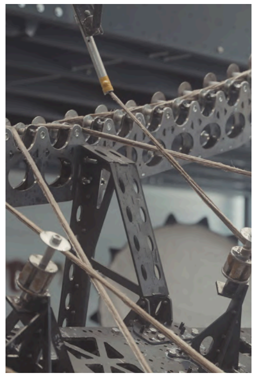


fig.05-24: cfw- frame

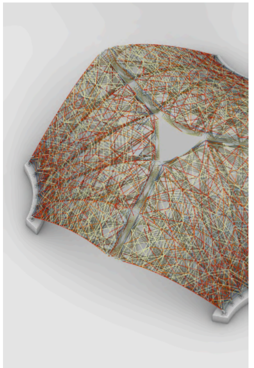


fig.05-25: structure overview

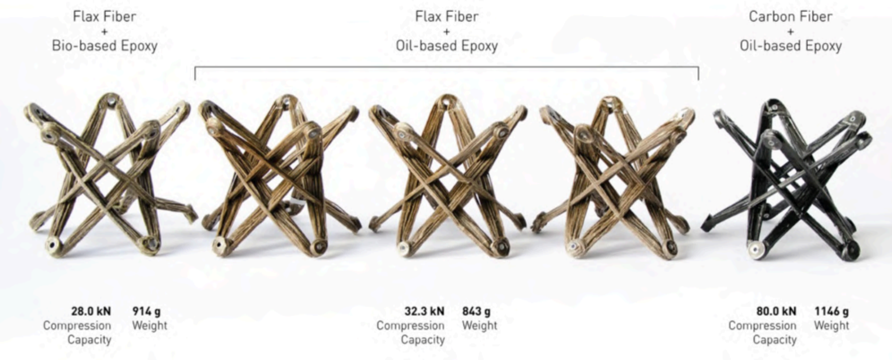


fig.06-26: resin overview


fig.05-27: livMatS pavlion in Freiburg, Germany

fire-retardant, smolders

short growth cycle (125 days)

low cost for material

lightweight

high stiffness

CO2 sequestering

local production (Europe)

low embodied energy

good mechanical properties

vibration absorption capability

thermal recycling

form freedom

pros

lack of experts

complex computational design

resin needed

absorbs water

so far only permanent structure

can not be used under water

cons

research question: how can biofibers, such as hemp and flax, be integrated in a sustainable architectural construction?

how to handle materials ? what is sustainability in regards to materials?

analysis design methods

research answer: panels, cast in place, insulation, textiles, spun yarn

research subquestion: how can this be utilized to enhance awareness and promote education regarding the benefits and applications of biobased materials?

finding from through winding

Similar to approaches inspired by nature, the art of winding in architecture requires hands-on experimentation. Given the ongoing discussion regarding form versus tectonics in the realm of materiality, there is a growing need for both experimental and technical comprehension. Understanding the various fabrication techniques is crucial to discover how they can be manipulated, processed, and applied for a specific purpose (Schröpfer, 2012).

The term "winding" signifies the preparatory phase that precedes weaving. The fundamental distinction between winding and weaving lies in their respective actions: winding involves the act of wrapping something around, whereas weaving is a more elaborate process that entails creating woven material on a loom.
While winding sets the stage by arranging or encircling materials, weaving is the transformative process that results in the creation of woven fabric, typically achieved on a loom. Each step plays a vital role in the overall textile production, with winding laying the foundation for the subsequent intricacies of weaving (Winding Vs Weaving, 2017).
Molecular fibers serve as the foundational elements, possessing the ability to be wound and woven, ultimately resulting in the creation of intricate three-dimensional patterns. When going into the volumetric characteristics, these fibers proove themselves to be as both delicate and lightweight, featuring expansive surfaces (Sauer et al., 2023).

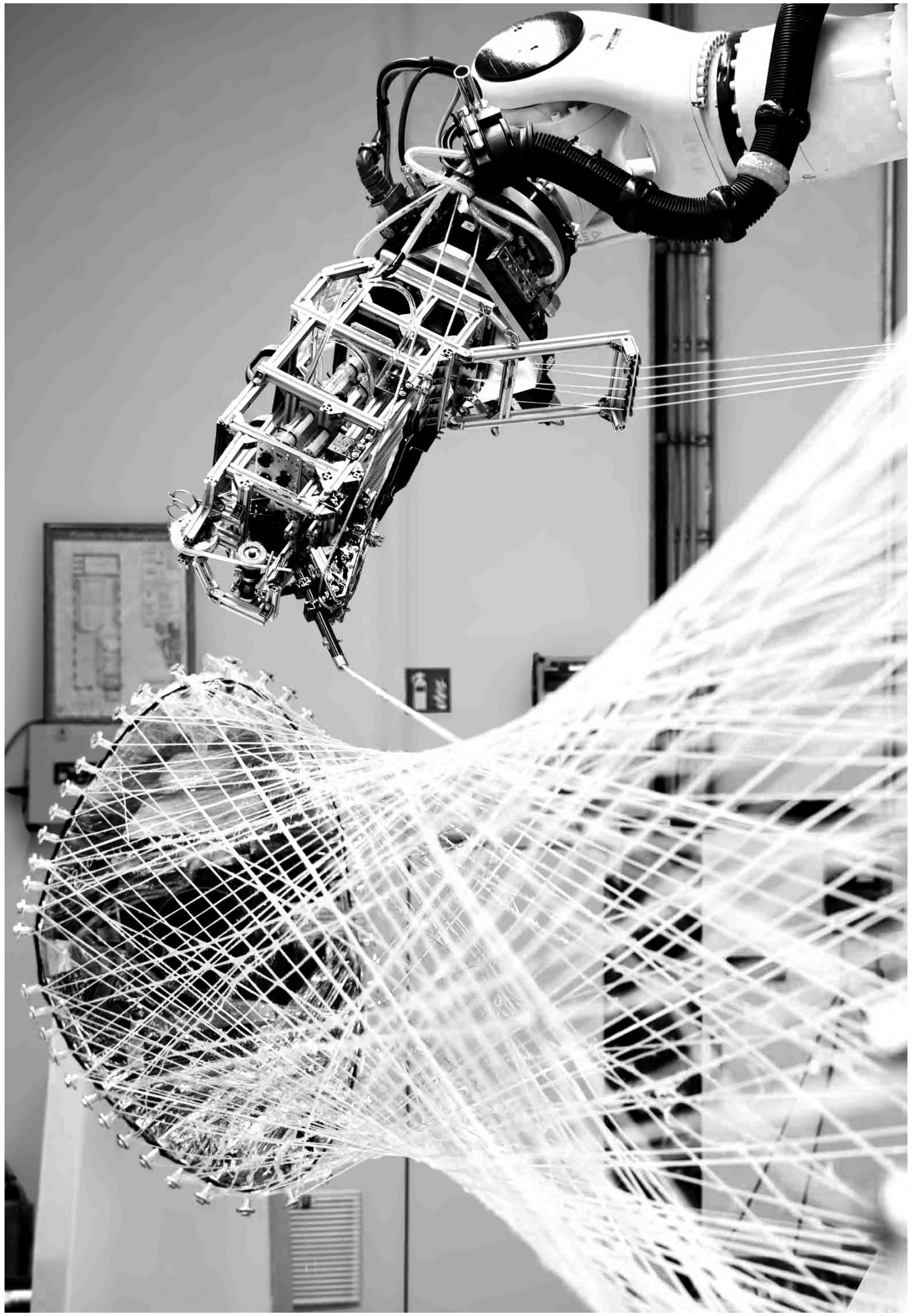


fig.06-01: cyber-physical robotic coreless filament winding in operation: robotic end-effector winding glass fiber tows

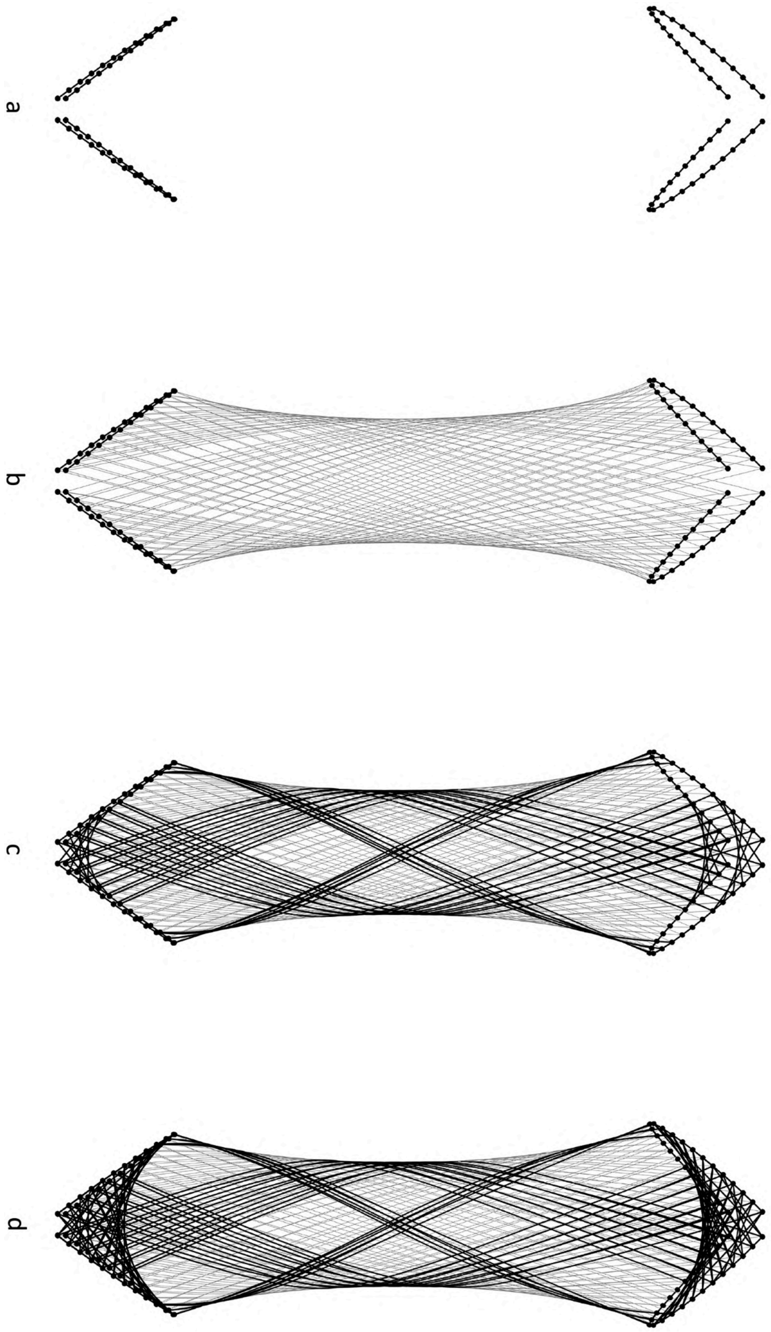


fig.06-02: component fiber layup

Coreless filament winding (CFW) is a unique method to construct large monocoque structures, while simultaneously allowing for the creation of smaller components and elements that can be seamlessly interconnected later. When external molds or structures are introduced and interconnected with the fibers, the term used is a hybrid CFW construction (Mindermann, 2022).

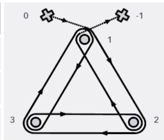
The final configuration of a structure is defined by the specific winding patterns and resulting syntax employed in the process. The spatial configuration of individual anchors, to which the impregnated fiber is woven, determine the shape of the final element. In hybrid structures, these fibers also engage with the introduced non-fiber elements. (Mindermann, 2022).

The minimal framework utilized in coreless filament winding stands for a significant flexibility in shaping the geometry of the final product. In this method, the interaction among subsequently laid fibers is essential, each characterized by a diamond-shaped basic unit that serves as a foundational building block. The manipulation of these fibers begins with this fundamental unit, allowing for the creation of diverse and complex geometries. The interplay of fibers during the winding process creates a synclastic surface, where the first tensioned fibers lie atop one another, forming a reciprocal deformation (Knippers et al., 2016).

The design language of Coreless Filament Winding , as previously mentioned, is determined by the winding setup. Specifically, it is characterized by straight connections between nodes. Within the fiber network, distinctions can be made among nodes, segments, and crossings. A segment is described as an "undisturbed fiber orientation" (Mindermann, 2022), positioned in alignment with the fiber direction. Nodes encircle the anchor to facilitate load transfer to the material, while crossings denote fiber intersections situated away from anchors.

Essential to understanding this technique is the concept of winding syntax, which denotes a specific sequence in the winding process. This methodology necessitates a material-driven design approach, wherein the final geometry emerges from the interweaving and layering of fibers, each following a predetermined sequence. In essence, the coreless filament winding process the interplay of form and material results in a freedom of structures that embody both aesthetic appeal and functional integrity (Mindermann, 2022).

	Winding Plan								
Winding Step	0	1	2	3	4	5	6	7	8
Winding Syntax	0	1	2	3	1	3	2	1	-1
Hooking Syntax	-	U	U	U	U	X	X	U	-



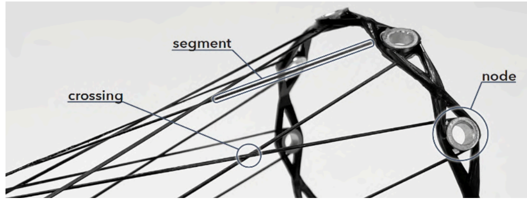


fig.06-03 & 06-04: winding plan and fiber net primitives

The inherent lightweight design and high stiffness of lattice structures make them more suitable for Fiber-Reinforced Polymer (FRP) constructions compared to truss-like structures. Fiber Reinforced Polymer are "material(s) consisting of reinforcement fibers, polymer resin, and additives to achieve the desired performance properties"(*as used in the LivMats pavilion*)(Creative Composites Group, n.d.).
Frei Otto recognized the potential of these lattice structures and demonstrated how complex buildings could be achieved without relying on computational design (Cabrinha et al., 2019)(Otto et al., 1995).

Lattice construction aligns to the principle of winding, creating a woven shell where individual layers are interconnected by wrapping the intersections together. The grid-like pattern of construction forms a diagonal arrangement, which can be further categorized into diagrids and gridshells. In a gridshell, form-finding is dictated by the boundary of a curve. Long spans result in curved surfaces, ultimately forming a shell-like structure. Experimental methods such as soapskin, hanging chains, or suspended models (see chapter design methods form-finding) play a crucial role in shaping the construction's form without computational design. On the other hand, diagrids integrate gravity-bearing vertical elements with the lateral system (Cabrinha et al., 2019).


fig.06-05: diagrid FRP structure


fig.06-06: gridshell FRP structure


fig.06-07: vyksa steel Production hall gridshell structure

fig.06-08: research pavilion 2012 spanning 8 meters and 4mm shell thickness

fig.06-09:research pavilion exosleket

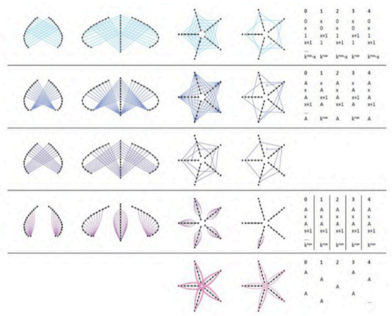


fig.06-10: winding syntax

„the exoskelet“

In 2012, the Institute of Building Structures and Structural Design (led by Prof. J. Knippers) and the Institute for Computational Design and Construction at the University of Stuttgart collaborated to construct a design that shows a distinct combination of an exoskeletal form, fiber orientation, and matrix.The fibers were arranged on a temporary, lightweight, linear steel frame with defined anchor points. Tensioning between these anchor points created an isotropic fiber structure, enabling uniform load distribution in all directions (ICD/ITKE Research Pavilion 2012, Institute for Computational Design and Construction, University of Stuttgart, n.d.).

fig.06-11: assembly of lightweight individual elements

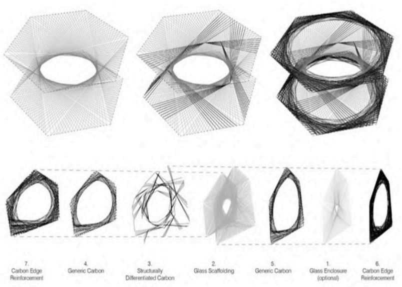


fig.06-12: individual winding layers

„the hammock“

The bionic research pavilion, developed by the Institute for Computational Design and Construction (ICD) and the Institute of Building Structures and Structural Design (ITKE) at the University of Stuttgart, features a double-layered structure connected by column-like doubly curved support elements. The winding process involved six individual layers of fiber, resulting in the fabrication of 36 elements covering an area of 53 square meters and a volume of 122 cubic meters. The system demonstrates morphological adaptability (ICD/ITKE Research Pavilion 2013-14, Institute for Computational Design and Construction, University of Stuttgart, n.d.).

fig.06-13: research pavilion spatial layout

fig.06-14: research pavilion 2014, bubble structure

fig.06-15: winding syntax

fig.06-16: pneumatic formwork

„the bubble“

The research pavilion from the Institute for Load-bearing Structures and Structural Design (ITKE) at the University of Stuttgart, from 2014/2015 takes strong reference from the study of biological construction processes, particularly the air bubble created by a water spider. The use of pneumatic formwork serves a dual purpose as both a structurally functional element and an integrated building skin (ICD/ITKE Research Pavilion 2014-15, Institute for Computational Design and Construction, University of Stuttgart, n.d.).

fig.06-17: monocoque winding syntax

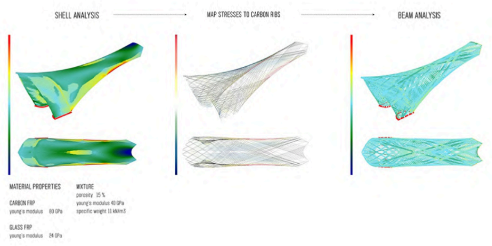


fig.06-18: shell stress analysis

„the hammock“

In 2016, the cantilevered structure, a result of collaboration between The Institute for Computational Design and Construction (ICD) and the Institute of Building Structures and Structural Design (ITKE) at the University of Stuttgart, explores natural long-spanned structures inspired by the leaf miner moth. The design integrates a bending-active substructure with coreless wound fiber reinforcement, forming a cohesive composite winding frame that spans about 12 meter (ICD/ITKE Research Pavilion 2016-17, Institute for Computational Design and Construction, University of Stuttgart, n.d.).

fig.06-19: research pavilion 2016, cantilever

fig.06-20: canopy diagrid pavillion

fig.06-21: slab and column interaction

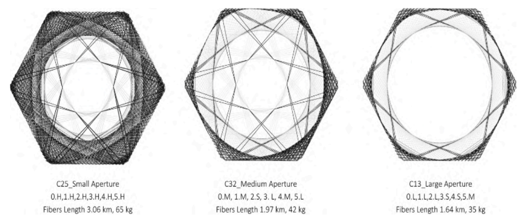


fig.06-22: winding syntax

„the canopy“

The winding method developed in a collaboration between the Institute of Building Structures and Structural Design (Prof. J. Knippers), the Institute for Building Technology and Climate-Friendly Construction at the Technical University of Munich (Prof. T. Auer), and the Institute for Computational Design and Construction (Prof. A. Menges, M. Dörstelmann) is designed to utilize fibers, enhancing their strength as woven structural components. With this innovative approach, a diagonal canopy was created in 2017 consisting of 40 hexagonal component cells over an area of 200 square metres (Elytra Filament Pavilion, Vitra Campus, Institute for Computational Design and Construction, University of Stuttgart, n.d.).

fig.06-23: buga pavilion, membrane

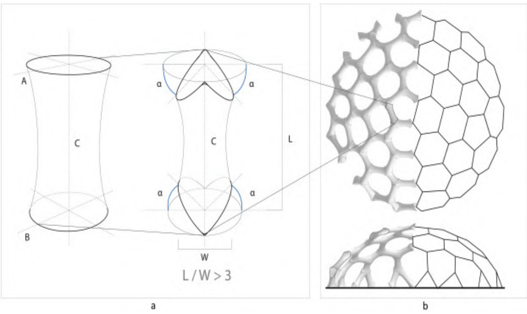


fig.06-24: buga pavilion, skeleton

„the skeleton“

The BUGA fibre pavilion, which was built 2019 in Heilbronn, is inspired by biomimetic research. Designed by the Institute for Design and Construction (ICD) and the Institute for Load-bearing Structures and Structural Design (ITKE) at the University of Stuttgart, the pavilion consists of 60 carbon and glass fibre elements produced by coreless winding.
Enclosed with a prestretched ETFE membrane, the pavilion features a load-bearing framework that is exclusively crafted through robotic processes utilizing advanced fiber composites (BUGA Fibre Pavilion 2019 , Institute for Computational Design and Construction, University of Stuttgart, n.d.).

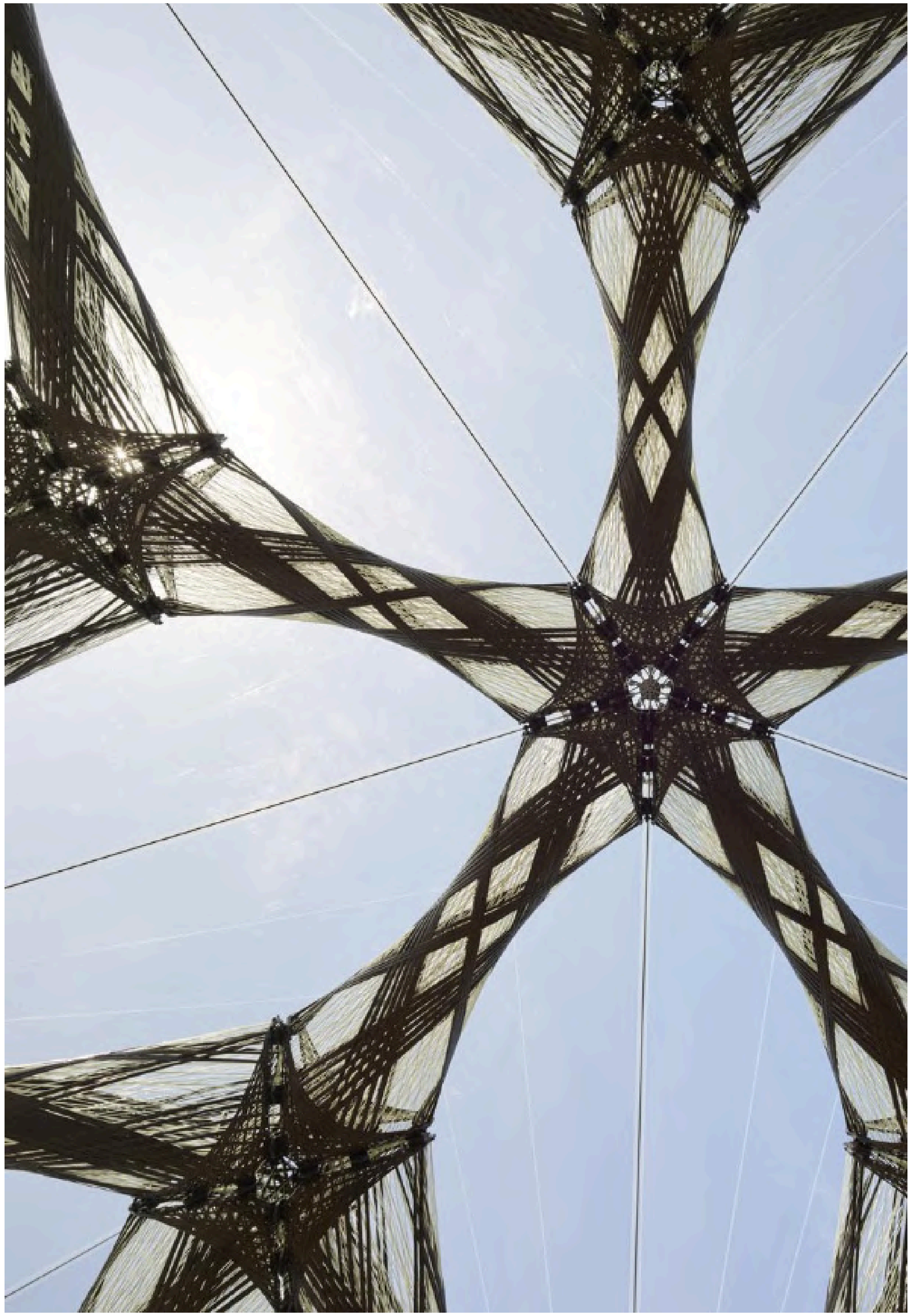


fig.06-25:buga pavilion bottom up view connector

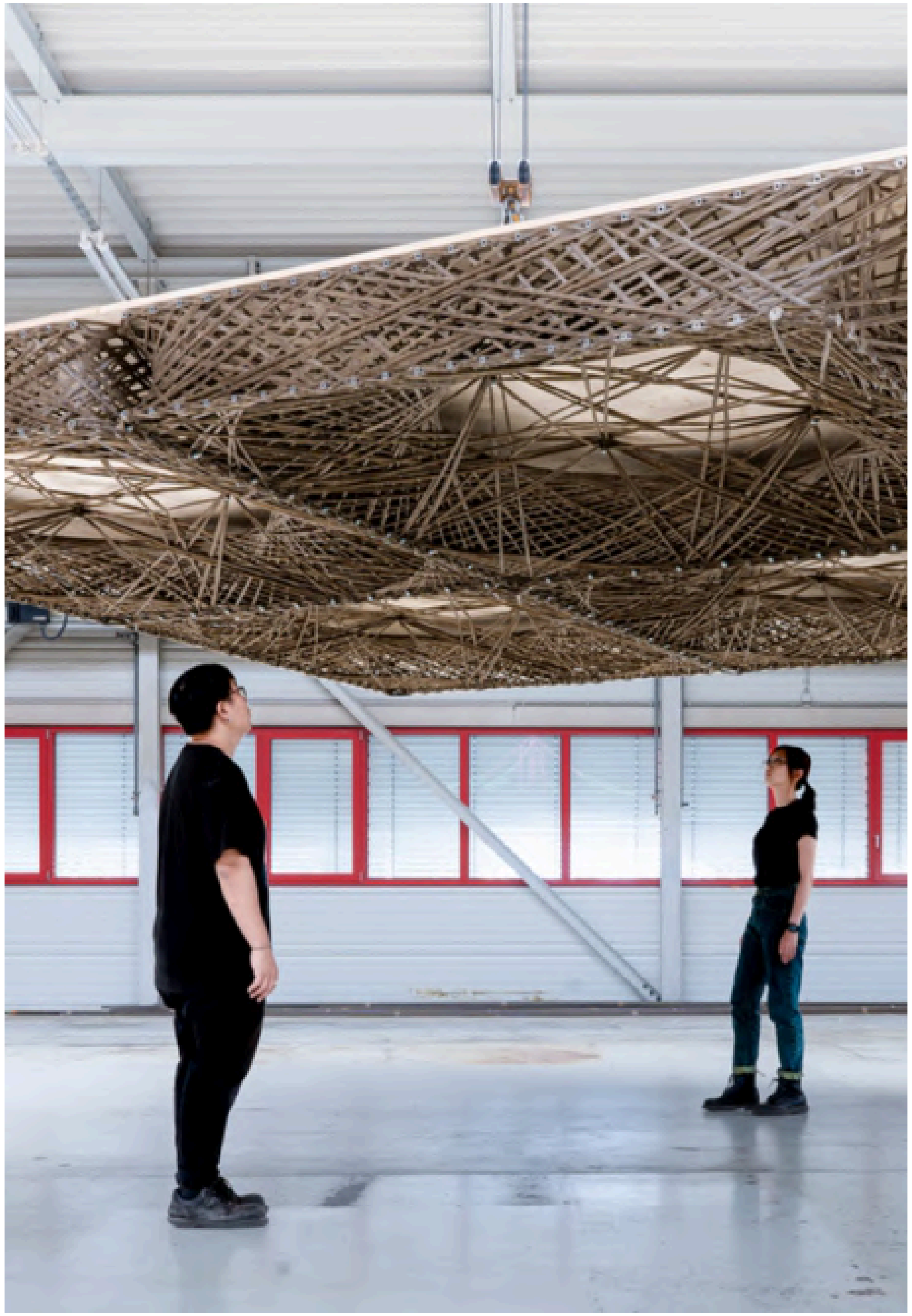


fig.06-26: fiber teconics hybrid cfw as ceiling

fig.06-27:fiber tectonics slab

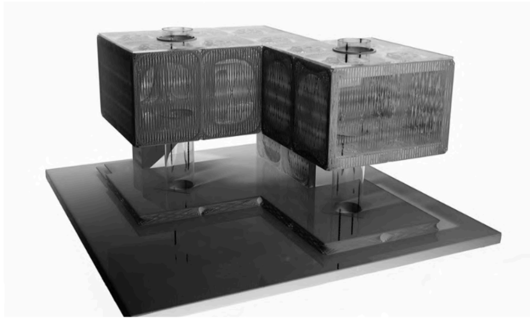


fig.06-28: fiber tectonics vision

„the slab“

Fibrous Tectonics, a project envisioned by the Institute for Design and Construction (ICD) and the Institute for Load-bearing Structures and Structural Design (ITKE) at the University of Stuttgart, was built in 2022 as an exhibition piece to demonstrate the potential of hybrid CFW structures. The hybrid coreless filament winding element integrates flax fibers with a wooden slab. Comprising four elements, the fibrous tectonic slab measures 5 by 5 meters in total. (Fibrous Tectonics, Institute for Computational Design and Construction, University of Stuttgart, n.d.).

research question: how can biofibers, such as hemp and flax, be integrated in a sustainable architectural construction?

analysis design methods

how to handle materials ? what is sustainability in regards to materials?

research answer: panels, cast in place, insulation, textiles, spun yarn

research subquestion: how can this implementation be achieved while addressing forthcoming challenges related to climate change, such as the rising sea level in the Hunze River Valley?

research subquestion: how can this be utilized to enhance awareness and promote education regarding the benefits and applications of biobased materials?

filament winding and fiber architecture

research result: flax fibers more suitable than hemp fibers as they posess similar properties to glass fibers

conclusion for design

The central question of how hemp and flax can be integrated in an architectural construction has led to diverse applications, including panels, cast-in-place methods, insulation, textiles, and spun yarn. These findings open up a range of possibilities for utilizing the unique properties of these biofibers in building processes.
The research's subquestion, focusing on utilizing these biofiber applications to enhance awareness and promote education about the benefits of biobased materials, revealed a promising avenue: finding form through winding. This innovative approach not only presents a new dimension to biofiber utilization but also serves as a means of raising awareness and educating various stakeholders.
In the context of coreless filament winding, it became apparent that hemp fibers do not exhibit the suitability required for effective fabrication. This insight refined the approach towards flax fiber integration, as they share similarities with glass fibers, and highlights the importance of considering the specific properties of each fiber in distinct applications.
Filament winding and fiber architecture emerged as key components of this educational strategy, as they authentically showcase the unique qualities of flax fibers. This insight is not only relevant to the coreless filament winding context but also contributes to a broader understanding of the comparative advantages of different biofibers.
In conclusion, the research has provided a comprehensive overview of the diverse applications of hemp and flax in sustainable architectural construction. While hemp may not be suitable for coreless filament winding, the varied applications of both fibers underscore the versatility of biofibers in contributing to a more sustainable future.

fig.07-01: 53°20'22.5"N 6°17'17.0"E

analysis design methods

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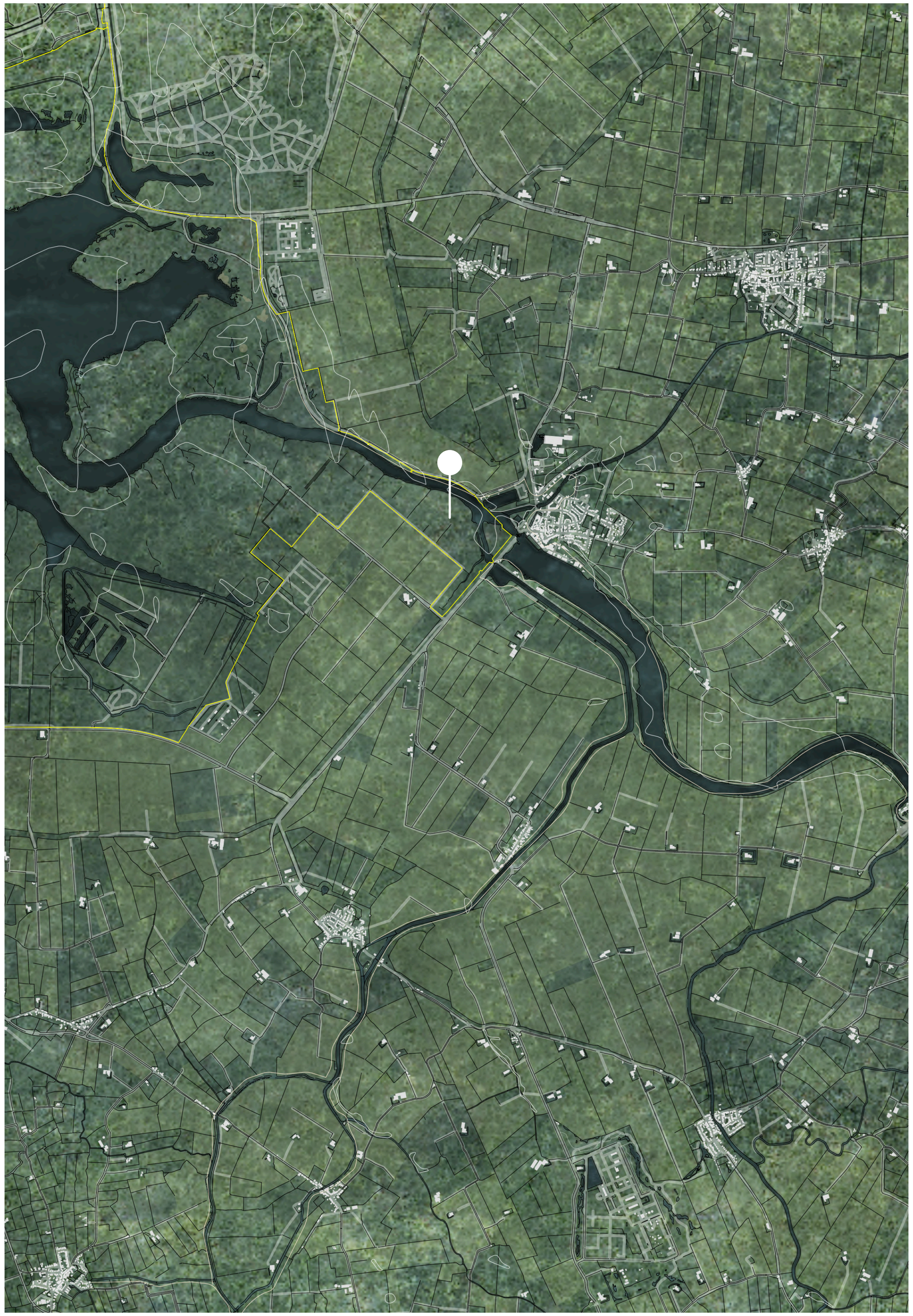

fig.08-01: siteplan

design brief

Despite the abundance of sustainable building materials, such as hemp and flax, there is an underutilization in the construction industry. The common materials, such as concrete, steel, brick, and timber, each have their strengths and weaknesses in terms of sustainability. Timber, for instance, is unique among the major materials as it can sequester CO_2, but is struggling with over-exploitation and decreasing sustainability due to excessive logging, resulting in a need of a greater variety of sustainable building materials.

research question

How can biofibers, such as hemp and flax, be integrated in a sustainable architectural construction?

How can this implementation be achieved while addressing forthcoming challenges related to climate change and rising sea levels in the Hunze River Valley? How can this be utilized to enhance awareness and promote education regarding the benefits and applications of biobased materials?

design assignment

The goal is to design a Biofiber Research Laboratory constructed using flax fibers and coreless filament winding, with the aim of fostering innovation, education, and public engagement. This multidimensional facility should integrate research and educational facilities. The objective is to create a dynamic environment that not only facilitates research in biofiber technology but also opens its doors to the public, in order to increase awareness and understanding of biobased materials.

location:	*zoutkamp, groningen, netherlands* *53°20'22.5"N 6°17'17.0"E*
year:	*2124*
materiality:	*flax fibers*
target-group:	*from general public to architects, to constructors, to investors, …*

programme

The programme for the Biofiber Research Center aims to seamlessly integrate research facilities with inviting and accessible educational spaces. The design prioritizes transparency, ensuring that visitors of all backgrounds can witness and understand the entire process of biofiber research.

Biofiber Material Testing Laboratory:
Laboratory equipped with instruments to conduct in-depth analyses of biofiber materials to explore mechanical, thermal, and environmental properties, ensuring a comprehensive understanding of material characteristics.

Coreless Filament Winding Room:
Specialized facility featuring advanced robotic elements for precision in biofiber fabrication using coreless filament winding technology.

Versatile Testing Room:
Dedicated space for thorough testing and assessment of biofiber-based materials to validate the performance and resistance of the materials under different conditions.

Visitor Center:
Welcome hall providing an immersive introduction to the world of biofiber research.Engaging displays, interactive exhibits, and multimedia presentations illustrating the journey from raw biofibers to end products.

Lecture Hall:
Modern auditorium designed for educational lectures, seminars, and presentations on biofiber technologies.

Workshop Spaces:
Flexible areas designed for hands-on workshops, encouraging active participation and learning.

Showroom:
Exhibition space showcasing diverse applications and products developed through biofiber research.

Collaborative Meeting Rooms:
Strategically designed meeting rooms to facilitate collaborative discussions, brainstorming sessions, and project meetings.

Transparent Open Laboratories:
Transparent design allowing visitors to observe ongoing research activities in the laboratories.
Educational tours offering insights into the scientific processes involved in biofiber research, promoting transparency and understanding.

Outdoor Learning Spaces:
Utilize outdoor areas to extend the educational experience with biofiber installations, outdoor workshops, demonstrations and green spaces.

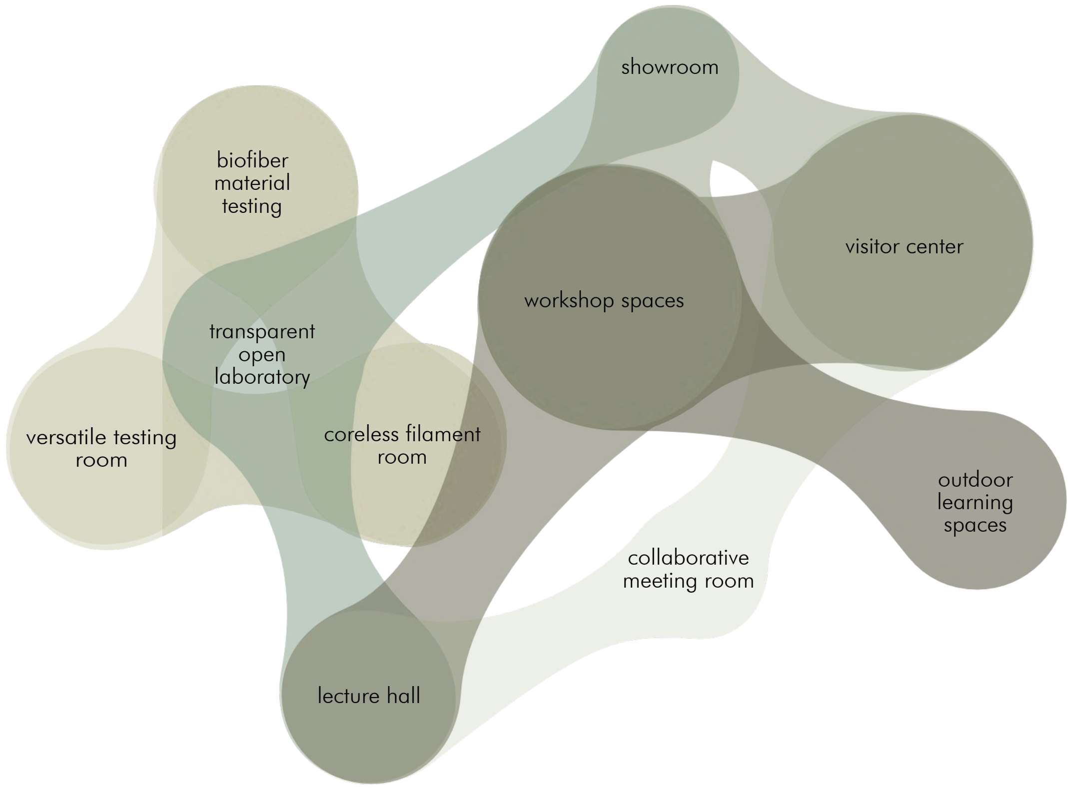

fig.08-02: programme biofiber research laboratory

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site analysis - zoutkamp

Zoutkamp, located in the province of Groningen in the northern part of the Netherlands, is approximately 31 kilometers northwest of the city of Groningen. Positioned along the shores of the Lauwersmeer, a lake forming the boundary between Groningen and Friesland, Zoutkamp boasts a rich historical significance rooted in its fishing industry, serving as a harbor for nearby Groningen.

The name "Zoutkamp" translates to "salted field," reflecting its historical role as a site where fish were salted before transport inland. The village features the picturesque Reitdiep canal running through it, and its charming harbor and historic architecture contribute to its allure. Over time, Zoutkamp has evolved into a popular tourist destination, attracting visitors with its maritime history, natural beauty, and a range of recreational activities.

site
grasland
farmland
water
street
buildings

fig.09-01: siteplan zoutkamp

fig.09-02: viewpoints around the shore of lauwersoog

In the pursuit of a fitting site for the Biofiber Research Center, an examination of Zoutkamp reveals a variety of recreational opportunities and scenic areas along the shores of Lauwersmeer. Taking into account the preservation of existing historic buildings and vital agricultural land, the choice of location and attention shifted to the south-western part of Zoutkamp, which lies outside the town.

The aim is to select a location that not only respects the historical context but also seamlessly integrates with the natural surroundings. Consequently, focusing on the southwestern area ensures the avoidance of disruption to existing structures and agricultural spaces. In addition, the strategic proximity to the city is of importance, as it fulfils a dual purpose: Not only does it contribute to greater awareness of the Biofibre Research Centre, but it also ensures its sustainable visibility within Zoutkamp. The deliberate choice of a location close to the city facilitates accessibility and promotes a closer connection between the research centre and the local community. The aim is to establish the centre as an integral part of the Zoutkamp landscape and to create a prominent presence that appeals to both residents and visitors. This deliberate integration is in line with the overarching goal of fostering a shared understanding and appreciation of biofibre research within the community and beyond.

After careful analysis of recreational activities and a site visit in November 2023, the chosen area, marked in fig.09-02, presents a harmonious blend of environmental elements. This region features a birdwatching viewpoint facing Lauwersmeer, an observation tower, and a harbor with a viewpoint and a trail. The integration of these three distinct viewpoints not only aligns with the natural beauty of the surroundings but also strategically positions the Biofiber Research Center as a prominent feature in the landscape, visible from both the city and the marked recreational spots.

fig.09-03: 53°20'14.2"N 6°17'46.7"E

fig.09-04: 53°20'28.9"N 6°17'22.8"E

ground analysis

The area located at coordinates 53.339584, 6.288055 in Zoutkamp is characterised by a sandy and loamy soil composition characterised by channels and deposits. The neighbouring farmland with its favourable conditions provides an optimal basis for flax cultivation.

In the design concept for this site, the influence of water needs to be integrated due to its proximity to a reed belt. The investigation of the neighbouring arable land revealed calcareous, marine clay soils without a mineral layer of soil and an immature subsoil.

sand

sea clay

sandy ridges

street

channels & inlays

fig.09-05: soil map of zoutkamp

fig.09-06: topography high points

fig.09-07: terp surrounded by water

safezone

riskzone

The map highlights dark patches indicating areas at risk from sea level rise, while lighter patches indicate elevated regions up to +3 metres above sea level.

In view of the growing concern about climate change and rising sea levels, it is clear how important it is to address the issue of water. Whether heavy rainfall, flooding, tidal influences or limited land availability, proximity to water requires strategic planning that considers the possibility of building on or with water.

Regarding the future scenario for the year 2124 in the area, sea level rise remains a major point of concern, especially if the traditional dikes no longer provide sufficient protection. Given the current elevation of -1 metre above sea level, any further rise in sea level would inevitably affect the region. However, an analysis of the topography shows that there are elevations in the area that reach up to +3 metres. I firmly believe that the Netherlands will not be completely flooded in 2124, but that the effects of sea level rise will manifest themselves in periodic tidal fluctuations. “Plan B is retreat. Give part of the land back to the sea.” (O’Leary, 2019).

In response, a landscape proposal could draw on historical methods in the region and proposes the construction of terps to mitigate the effects of sea level rise. This approach involves either incorporating a landfill to raise the structure or using a pile structure to raise the research centre above the tidal range. When using bio-based materials, it is important to remember that these materials absorb water. Strategies to address this issue are essential to ensure the resilience and functionality of the research centre under changing environmental conditions.

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material studies

In a material workshop, each student was tasked with independently exploring their selected biobased material to craft a unique laptop stand. The materials of choice for this project were hemp and flax shives, blended together to form a hempcrete composite. To enhance the structural integrity of the mixture, gypsum was selected as a binding agent. In addition, a wire reinforcement was incorporated into the design, and various sizes of shives were experimented with to achieve the desired characteristics.

fig. 10-01: hempcrete laptop stand

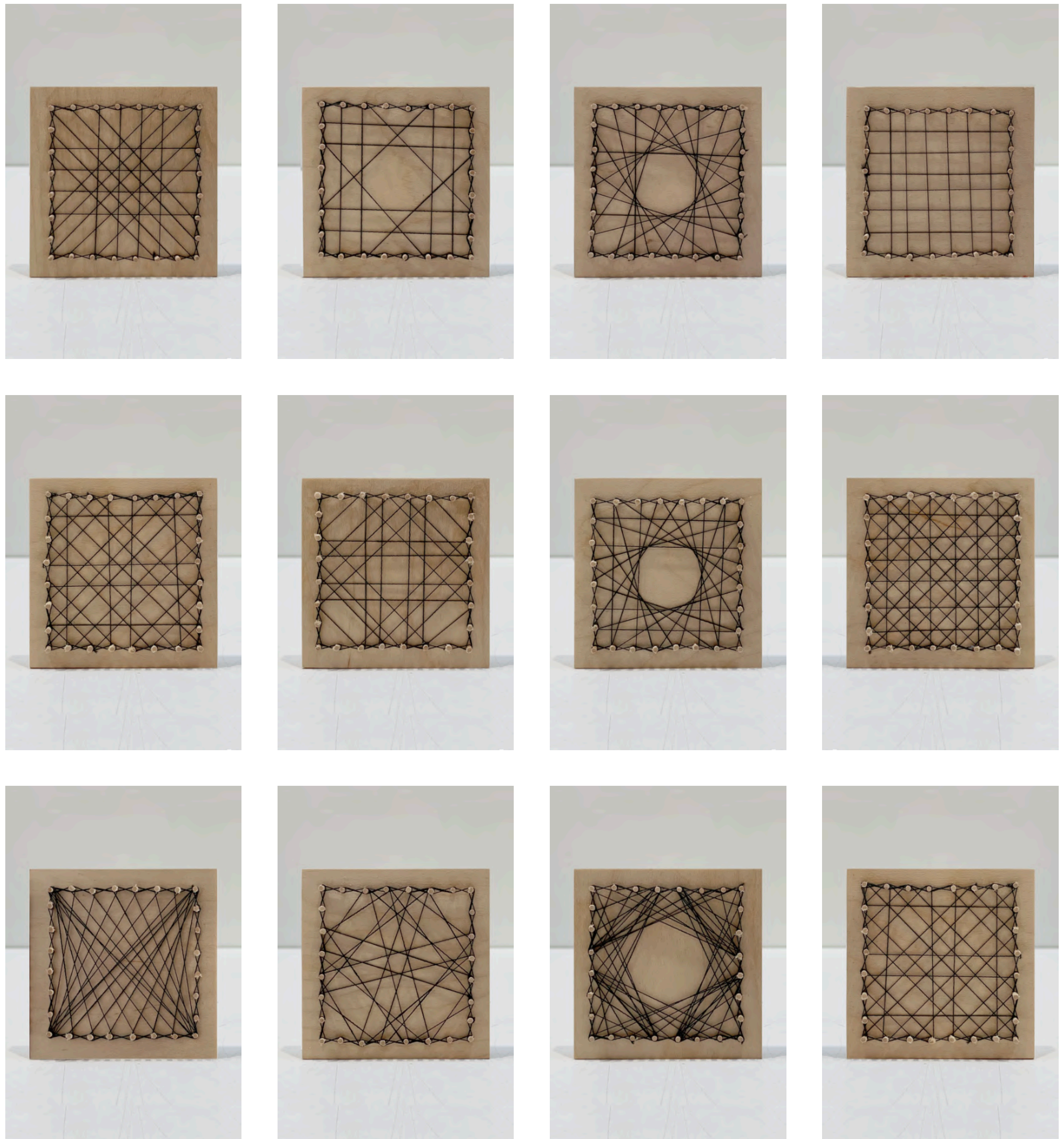

fig.10-02: winding patterns

winding studies

Experimental exploration of forms involves moving from conventional winding patterns to a variety of their combinations. In this study, a yarn was intricately wound between anchor points, following the organised structure of an 8 x 8 grid. This deliberate choice of grid adds a layer of systematic precision to the winding process and creates an interplay between the linear connections and the underlying grid structure.

formstudies

Coreless filament winding offers a broad spectrum of possibilities in shaping diverse forms. It extends the creative scope from crafting expansive individual cantilevering structures to combining multiple elements into a cohesive, larger form. This fabrication technique bestows a remarkable degree of freedom upon the designer, encouraging exploration and innovation in the pursuit of new possibilities. The inherent flexibility of coreless filament winding allows for an iterative and experimental design approach.

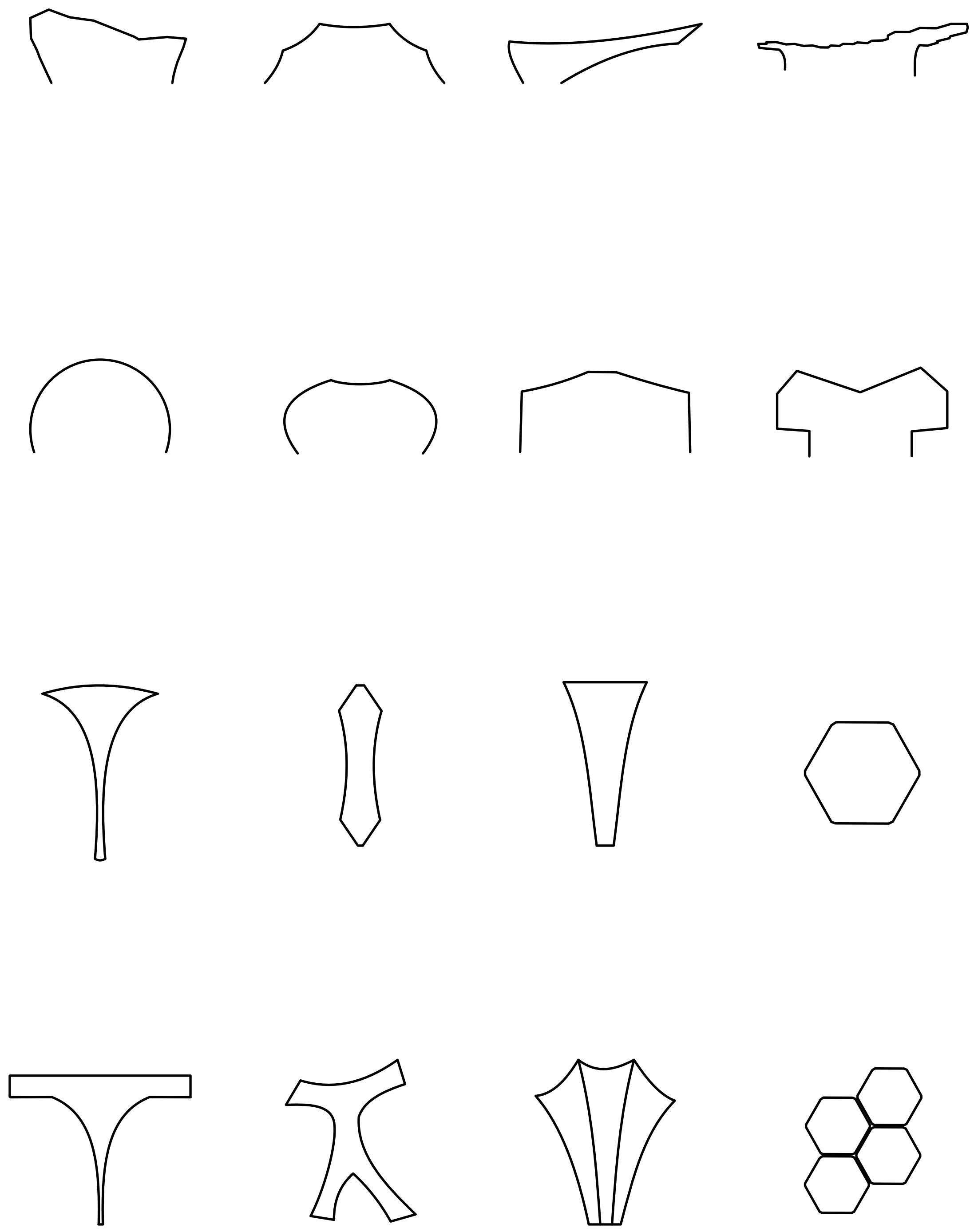

fig. 10-03: formstudies cfw

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relation of the graduation project to master track and programme

The relation between my graduation project topic, the studio focus, my master track, and my master program is evident in the cohesive exploration of sustainable architecture, technical design innovations, and the implications of climate change. My graduation topic centers around the investigation of hemp and flax as biobased sustainable materials, examining their implementation and understanding both the technical and aesthetic dimensions. Specifically, I am delving into how technical advancements and innovations align with the aesthetic principles of architecture and the inherent form language of these materials. This closely aligns with the studio's goal, which is to explore the relationship between technical design innovations and the challenges posed by climate change, emphasizing the architectural form language and aesthetics associated with these developments. This focus seamlessly aligns with my master track, providing a comprehensive approach to addressing the pressing issues of our time within the context of sustainable architecture.

research and design

The main focus of this research was to explore the integration of hemp and flax in sustainable architectural constructions. Despite the potential benefits of these bio-based materials, there is a gap in understanding their practical implementation in the construction industry. To address this, my study addressed two specific sub-questions. Firstly, it was investigated how the integration of hemp and flax can be realised in a thermally encapsulated building in the Hunze Valley, which is confronted with the challenges of climate change. Second, research and design aimed to explore ways in which this integration can serve as a tool to raise awareness and improve education about the benefits and applications of bio-based materials.

The research significantly influenced the design process. By examining the technical data and mechanical properties of hemp and flax, the study provided important insights into how these materials behave under various conditions. This knowledge was essential for making informed decisions about their application in sustainable architectural construction, ensuring that the design was both structurally stable and long-lasting.

Additionally, reviewing similar projects and understanding their limitations allowed the integration of successful elements into the design, thereby developing a combination that maximized the benefits of both hemp and flax.

Conversely, the design process also influenced the research. Through model studies and testing different combinations of hemp and flax, the design experiments provided practical insights that informed the theoretical research. The result of the research was, for example, that although hemp fibres are ideal for use in hempcrete as a filling material, they are structurally unsound. In contrast, flax fibres proved to be an excellent structural support material.

These findings were applied to the design trials and contributed to a deeper understanding of how these materials can be combined and used effectively. The process of designing, testing and refining the models ensured that both the research and the design evolved together. This feedback loop was crucial for validating the hypotheses, adapting the methods and ensuring the practical feasibility of the proposed design solutions.

In conclusion, the research and design processes were deeply interconnected. The research provided essential technical data, insights from existing projects, and strategies for climate resilience, all of which informed the design. In turn, the design process involved practical experimentation and application, which validated and refined the research findings. This symbiotic relationship ensured that the final outcomes were both theoretically sound and practically viable, advancing the integration of hemp and flax into sustainable architectural construction while raising awareness and improving education on the benefits of biobased materials.

approach and methods

The value of my approach results from the careful investigation and evaluation of hemp and flax as bio-based building materials in the context of durable architectural structures. I employed a multi-layered methodology that included several key components: extensive literature review, case studies, comparative analysis and performance evaluation. Firstly, the in-depth literature review provided a comprehensive understanding of the mechanical properties, environmental benefits and best practices associated with the use of hemp and flax. This theoretical foundation was further deepened by examining case studies of existing buildings incorporating these materials, providing valuable practical insights.

value, scope and implication

The relevance of my graduation work extends across multiple dimensions within the larger social, professional, and scientific framework. Socially, my investigation into hemp and flax as biobased sustainable materials holds significance as it addresses the growing awareness and urgency surrounding sustainable practices in architecture, both for the general public and for architects. By exploring how these materials can be implemented, my work contributes to the discourse on environmentally friendly construction methods, fostering a more sustainable built environment.

Professionally, the findings from my research carry implications for architects, builders, and designers seeking innovative solutions aligned with the principles of sustainability. Understanding the technical and aesthetic aspects of biofibers broadens the toolkit available to professionals, offering insights into creating structures that are both environmentally conscious and aesthetically compelling.
In the scientific realm, my work contributes to the ongoing exploration of biofibers and their application in architecture. Investigating the technical advancements and aesthetic considerations of these materials adds valuable knowledge to the scientific community, enhancing our understanding of sustainable building practices and their potential impact on climate change.

Overall, my graduation work serves as a bridge between social, professional, and scientific domains, offering practical insights into sustainable architecture and biofiber technologies, ultimately contributing to the collective effort towards a more sustainable future.

transferability

One approach that has significantly influenced the research is the use of hempcrete as an inner core to encase the typically hollow, flax-wrapped structures, providing insulation against heat, noise, odours and other environmental factors. The research and design results show the potential for fusing existing materials into innovative combinations. As outlined in the introduction to my research, the focus is not just on finding a single perfect or sustainable material, but rather on finding optimal combinations of different materials to maximise their positive properties. This approach aims to enhance and utilise the unique benefits of each material. Furthermore, the role of design in raising awareness and education about bio-based materials emphasises the tangible impact and potential of research.

challenges and solutions

It should be noted that the disadvantages of the project lie in the cost, which is due to the infrequent use of the materials and the lack of expertise and specialised machinery. However, it is important to recognise that the main aim of the project was not to design an economically affordable sustainable building. Rather, it was to demonstrate the potential of biofibres and inspire others to use them in order to increase their uptake and ultimately reduce costs.

considerations

However, navigating the design and research process presented a challenge due to the time constraints of my final project. The versatility of flax as a building material offered numerous possibilities that required careful decision making in the design process. In order to maintain focus and feasibility, I had to set boundaries and constantly re-evaluate my approach to ensure the project remained viable and coherent. The potential also seemed limitless in terms of architectural realisation and location. Nevertheless, my aim was to find a balance between innovation and feasibility and to ensure that the integration of flax into a thermally insulated building remained logical and comprehensible. Clarity and legibility were paramount in both the design outcome and the project presentation, where I took an approach that prioritised understanding and connection to the environment.

towards p5

The final stage of this project is the production of models. This step is crucial as it allows me to visualise and integrate all the carefully considered elements and provide a tangible representation of the project in reality. Using these models, I can evaluate the functionality, design and practical application of the theoretical ideas and determine whether the expectations and objectives are being met. With the help these models, I can identify potential improvements and refine my approach, ultimately leading to a more polished and effective end product.