# A NEW VISION ON LIGHTWEIGHT FIBER-BASED BUILDING SYSTEMS USING CORELESS-FILAMENT WINDING

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***ABSTRACT***

The building industry's emphasis on cost-driven standardization has led to more waste, prompting a need for resource-efficient methods. While coreless-filament winding (CFW) with materials like flax fibers show promise, a research gap is present. This study explores how computational design, coupled with coreless-filament winding, can create modular, demountable, and aesthetically valued fiber-based building systems. The methodologies chosen are research-by-design and prototyping, which generates various design options that are supported by literature and insights from an expert in the field. The viability of flax fiber-based building systems, using CFW, relies on the intended function. While flax is optimal for structural and thermally insulated elements, addressing weatherproofing and flammability necessitates a combination of different fiber types in bespoke fibrous tectonic structures.

***KEYWORDS:*** *Bespoke fibrous tectonics, Biobased, Computational design, Coreless-filament winding, Dematerialization, Demountability, Flax fibers, Fiber-based building systems, Modularity.*

## I. Introduction

One of society's most pressing environmental issues is the rising demand for new resource efficient building materials and methods (ECESP, 2021). However, rather than reducing the materials utilized, innovations in the building industry focused on lowering the cost through standardization, resulting in significant waste, pollution, and gas emissions. This trend resulted in a slight increase in efficiency, but in comparison with the manufacturing industry the building industry is falling behind (Mckinsey, 2017) [See appendix 1]. A need for an increase in resource efficiency of structures and the productivity of our building processes is key for the future of the industry. According to INJArchitects lightweight constructions are from an ecological, social and cultural standpoint beneficial to our society. Due to less waste material, feasibility to disassemble and recycle or compost and the production and assembly results in increased employment (INJ, 2023). Although steel has been an efficient material to use in lightweight structures the introduction of steel in the industrial revolution has started the exhaustion of our planet and therefore new materials need to be researched thoroughly to reverse this trend. Lightweight structures can also be constituted from fibrous materials, such as: carbon-, glass- and remarkably flax fibers. These materials have higher tensile strengths, are lighter and emit less $CO_2$ than steel [See Appendix 2]. Lastly, research has shown that flax fibers can be harvested on soils in North-Western Europe (Vleesschouwers, 2020). In conclusion, based on the considerations presented, flax can be considered the most potent material for constructing lightweight structures. Furthermore, the manufacturing industry has been capable of increasing their production efficiency due to the large quantities it can produce with minimal variations. The building industry mostly relies on the variations in end products and therefore cannot utilize the same techniques. As Jan Knippers, Professor at the Institute of Building Structures and Structural Design on the University of Stuttgart, states: "we as architects and engineers have to develop our own fabrication processes adapted for the needs of architectural and building construction" (Pérez, Guo, & Knippers, 2022). A technique that uses the material characteristics of fibers, such as Flax, is coreless-filament winding (CFW). Although the introduction of coreless-filament winding is optimistic, a research gap is present. The aim of this study is to close the knowledge gap on how to design and fabricate lightweight, material-efficient (dematerialized) modular, aesthetically valued (bespoke fiber tectonics) load-bearing structures for large spans that can be integrated with building envelopes to form fiber-based building systems using the coreless-filament winding technique and regionally harvested flax.

# II. Methodology

## 2.1 General overview of the methods

Several research methods have been used to answer the formulated research question: *"How to create lightweight fiber-based building systems for large open spaces from (regionally harvested) flax fibers using coreless-filament winding, whereby bespoke fibrous tectonics, dematerialization and modularity are considered as guiding themes?"*

The main methodologies chosen are research-by-design and prototyping which generates various design options. This is supported by literature review to gather relevant information on the material characteristics and performances of (flax) fibers and the life cycle of flax as a building material. A case study is conducted to analyze different pavilions constructed by the University of Stuttgart on structural typology, structural elements, winding syntaxes and structural connections to gather vital information for the research-by-design and prototyping phase. This research expands on the existing structural and architectural theories on fibrous elements constructed using the coreless-filament winding technique and proposes potential solutions based on parameters derived from these theories in order to generate fiber-based building systems.

## 2.2 Framework with sub-questions

The research is segmented into three distinctive interrelated themes i.e. dematerialization & decarbonization, production of fibrous tectonics and modularity & demountability. The main research question is subdivided into five sub-questions which are briefly explained, and the chosen methods used to answer these questions are elaborated in the next paragraph.

**Dematerialization & Decarbonization**
Through literature study (quantitative) the material characteristics of (flax) fibers will be examined whereby the findings are used in a comparative analysis of performances [See appendix 2] which results in various design preconditions that are relevant for using (flax) fibers with CFW to create dematerialized fibrous structures.

- *What are the characteristics of (flax) fibers that need consideration to use the material with the coreless-filament winding technique to achieve dematerialized fibrous structures?*

The cycle of flax from crop to filament winding material is researched through literature study (quantitative) to gain knowledge on the life cycle of flax with decarbonization in mind and results in preconditions that are relevant in the fabrication of fibrous structures using CFW.

- *How are flax fibers harvested, processed, and finalized to be used for coreless-filament winding and how can the biodegradability of the end product be ensured?*

**Production of fibrous tectonics**
A selection of pavilions constructed by the University of Stuttgart over the past decade have been selected which will be examined through case study analysis (qualitative) [See appendix 4]. This to gain knowledge on how these fibrous structures are constructed using the coreless-filament winding technique. Additionally, these cases will aid the next phase of research by design and prototyping as a guiding reference for dematerialized modular fibrous structures. Furthermore, an

interview will be conducted with Dr. Julian Fial, Head of Production & Development at FibR, a construction company that creates load-bearing elements, facades, and interiors using architectural fiber composite structures to get more insight in how to work with the material using the coreless-filament winding technique and upscale the approach to other building elements.

- *How can the fabrication technique of coreless-filament winding be optimally used with flax and other types of fiber-based materials resulting in dematerialized modular structures characterized by fibrous tectonics?*

**Modularity and Demountability**
Research by design and prototyping (qualitative) will be used to generate various design options of fiber-based building systems. This results in various combinations of structural elements with fibrous building envelope types which aim to be thermally insulated, weatherproof and structurally optimized [See appendix 10]**.** Several prototyping setups are and constructed to be able to experiment with various fibrous structures and -building systems [See appendix 9].

- *How can these structural and non-structural fibrous elements be combined in a modular and demountable way, while being thermally insulated, weatherproof and structurally optimized, to form fiber-based building systems?*

Lastly, the use of computational design in the fabrication and design process of the fibrous structures is analyzed through literature study (quantitative), the previously mentioned case study analysis and through digital prototyping [See appendix 8]. This to gain knowledge on how computational design can help during the fabrication process and achieve dematerialization, form freedom and structure optimization in the design of fibrous structures.

- *How can computational design aid in creating fibrous structures that utilize dematerialization, are structurally optimized for the shapes needed for the program and enable form freedom?*

# III. Results

## 3.1 Dematerialization & Decarbonization

In this section the paper focuses on the material characteristics and performances of flax in comparison with other fibrous filament winding (FW) materials and the life cycle of flax as a building material. The questions formulated will help understanding why flax can help decarbonate and dematerialize the fabrication of lightweight structures.

### 3.1.1 What are the characteristics of (flax) fibers that need consideration to use the material with the coreless-filament winding technique to achieve dematerialized fibrous structures?

Natural fibers can be classified: most natural fibers can be obtained from lignocellulosic fibrous plants and are categorized based on their origin of source: the seed, stalk, root, grass, stem, fruit or leaf, respectively. The natural filament winding materials that have been compared in table 1 [See appendix 2] come mostly from the plant's stem (Radkar, 2018). The flax plant, scientifically known as *Linum Usitassimum L.,* is primarily made up of three distinct parts: the root, stem and flower. The flax fibers are located within the stems, are distributed evenly into 10 segments lengthwise and are interconnected. The filament is grouped in bundles and are surrounded by a holding tissue consisting of pectin and lignin (Kozłowski & Mackiewicz-Talarczyk, 2020). Cellulose is the primary substance of the fibers which determines the fiber strength (Mohamed & Hassabo, 2015). Pectin is a crucial component that keeps the fibers together and also influences its shine and roughness. The effectiveness of removing pectin compounds during initial processing is crucial in determining the capacity to divide the fiber and, consequently, the quality of the fiber and its appropriateness for spinning (Kozłowski et al., 2010a,b).) Lignin causes the cellulose to be firm. The presence of lignin during processing makes the fiber more susceptible to breakage, resulting in a decline in mechanical properties such as tenacity and resilience. Therefore, lesser quantities of lignin result in more durable fibers (Brutch, et al., 2008).

For the use of flax as filament winding material its characteristics are compared, illustrated in table 1 [See Appendix 2], with other (FW) materials on the basis of structural-, fire-, moisture- and thermal behavior, aesthetics, sustainability and durability to evaluate several design preconditions for using it. Structurally, on the aspects of tensile- and compression strength, elasticity and density, flax has good qualities in comparison with other (FW) materials. It has the highest tensile- and compression strength among the natural fibers, but carbon- and glass fiber outperform flax more than double on tensile strength. Carbon fiber has a higher compression strength, but in comparison with glass fiber flax outperforms it by a great margin. Flax is the stiffest natural fiber, although carbon- and glass fiber are much stiffer. The density of flax is equally light to other natural fibers and lighter than carbon- and glass fiber. Flax, and other lignocellulosic fibers, are easy to ignite and flammable due to their high cellulose content. Flax has the highest burning point among the natural fibers, but carbon- and glass fiber have higher burning points. The flame-retardance can be improved through treating with resin (Kozłowski, et al., 2020). However, according to Dr. Julian Fial [See appendix 6] flax fibers can never be truly non-flammable due its natural flammability and the dematerialization of the structure causes the elements to be minimally voluminous which reduces its fire-retardance. As also in the case of other natural building materials, such as glulam columns, the thicker the more fire-retardant the structure becomes. Tests from FibR on their carbon fiber structures achieved a B1 fire rating which means it's fire-retardant, but does not specify how much. Basalt fibers can be utilized as a fire-retardant material due to its 99,9% non-organic composition. The most important issue concerning natural fibers is its hydrophilicity (moisture behavior), which means that it has a tendency to mix with, dissolve in, or be wetted by water (Radkar, 2018). Flax and hemp are good thermal insulators due to their hollow stem structures. Carbon fiber has the highest thermal conductivity which resonates into more heat conducted. Flax and hemp have a soft, shining and flexible texture and sisal is rougher. Acoustically flax has a good sound absorption, carbon fiber has the lowest sound absorption coefficient. All natural fibrous materials are biodegradable and eco-friendly due to their natural origin. Although, in the case of any modifications to the materials, such as resin treating, the biodegradability might be altered. Lastly, flax is not UV- and chemical resistant, but this can be optimized by resin treatment. The aforementioned characteristics demonstrate the genuine potential of flax as a filament winding material for utilization in lightweight fiber-based building systems.

### 3.1.2 How are flax fibers harvested, processed, and finalized to be used for coreless-filament winding and how can the biodegradability of the end product be ensured?

The flax plant is harvested once it reached a height of roughly 100cm, which typically takes around 100 days of growth. The prerequisites for preceding crops are less demanding, and flax can be cultivated consecutively following any crop which provides justification for implementing crop rotation (Walkowski, Ladek, & Piotrowska, 1998). However, flax cultivation is limited to a cycle of 7 years on a given plot due to the potential for crop diseases. The life cycle of flax as a building material is illustrated in figure 1 [See Appendix 3]. When the flax plant blooms the plant is fully grown and farmers pull the flax from the ground. Shortly after being pulled, the stems promptly collapse horizontally behind the machine, forming two parallel rows. Following the act of harvesting, the flax must undergo the process of degumming or retting which is the extraction of fiber from the hardwood core (Kozlowski et al., 2005, 2006a, 2006b). The flax plants are deseeded and compacted into bales. Following the completion of the harvesting cycle, the subsequent steps are scutching, and hackling (McIntry, Denton, & Daniels, 2002). The extracted flax fibers can be utilized for spinning (Sultana, 1991). The thread can be twisted, which refers to the interlacing of two or more yarns or utilized as roving without the need for spinning which is used for the coreless-filament winding technique. The treatment of the fibers may differ based on the intended objective. Generally, the Life Cycle Assessment (LCA) of various products has demonstrated that natural fiber composites outperform other materials in terms of their environmental impact throughout usage and end-of-life evaluation (Pérez, Guo, & Knippers, 2022). However, it is important to note that the overall environmental impact, i.e. biodegradability and sustainability, depends heavily on the production phase and the modification of the material. Lastly, according to Dr. Julian Fial [See appendix 6], biodegradability of natural fibers is the main challenge for using it for structures that will stand for decades. Therefore, the end of life of fibers can also be seen through another lens. As Dr. Julian Fial stated, the modular structures created using the coreless-filament winding technique can be firstly demounted and reused for other buildings. Secondly, at the end of its lifespan, the fibers [See appendix 3] can be upcycled through shredding to produce short fiber-based elements with other functions, such as insulation or particle boards. However, the feasibility of fiber recycling is depended upon the usage of a single fiber type during the winding process, as otherwise the fibers become inseparable.

## 3.2 Production of fibrous tectonics

In this section the paper focuses on the fabrication technique of coreless-filament winding. The key procedures to create the fibrous structures and the development of the technique over the last decade are discussed. The questions formulated will help to understand how the technique works, what kind of fibrous structures are created and how the technique achieves dematerialization.

### 3.2.1 How can the fabrication technique of coreless-filament winding be optimally used with flax and other types of fiber-based materials resulting in dematerialized modular structures characterized by fibrous tectonics?

It is important to acknowledge the increasing prominence of Robotic Filament Placement in various sectors, including industrial- and automotive manufacturing. While the use of RFP was increasing, a difficulty arose in accurately translating Fiber-reinforced polymers (FRP) to an Architectural scale. The intricate geometric variations required to fully utilize the material's potential, both at the individual component level and in the overall assembly, along with the large scale and numerous elements involved, sometimes makes customized solutions unfeasible. Thus, the University of Stuttgart has devised a "coreless" filament winding technique that forms the structure of the component by carefully manipulating the interaction between fibers, eliminating the need for pre-made winding mandrels or expensive molds. Coreless-filament winding identifies the need for the reduction or even elimination of formwork on the architectural scale (Prado, et al., 2014). The difference between mandrel- and coreless-filament winding is illustrated below in figure 1 and 2.

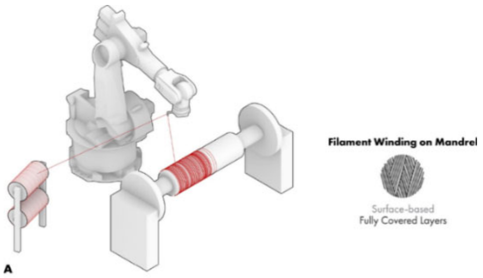


*Figure 1: Traditional filament winding on mandrel*
*(Duque Estrada, et al., 2020) Accessed 02 Dec 2023.*

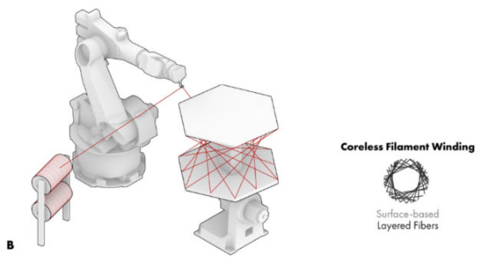


*Figure 2: Coreless-filament winding without a mandrel*
*(Duque Estrada, et al., 2020) Accessed 02 Dec 2023.*

In recent decades, the University of Stuttgart has initiated the use of this innovative technology with the ICD/ITKE Research Pavilion 2012 being among the earliest examples [See Appendix 4]. A singular robotic arm equipped with an external rotational axis was employed to fabricate a slender and sturdy monocoque framework of around 7 meters in width, length, and height. The dimensions and shape of the pavilion were determined by the capabilities of the robot arm and the 7-axis configuration, which had constraints when it came to constructing larger structures. Thus, the University of Stuttgart addressed these constraints by developing a framework that incorporated numerous smaller elements and advocated the production of highly distinct construction components, necessitating a substantially altered fabrication setup. The newly proposed fabrication setup is a continuous process where the shape of the building part is determined by the interaction of free spanning fibers between two boundary frames.

This allows for the creation of distinct building components with flexibility in design. The frames contain several distributed winding pins used for winding the fiber filament. Initially, a glass fiber arrangement is wrapped around to form the supporting structure of the beam. Subsequently, carbon fiber is strategically applied to areas of the structure where stress lines are present, illustrated in figure 3 below. Prior to winding, the filament is immersed in a resin bath, allowing the fiber filament to be impregnated. Once the mold has been cured, the robotic setup of the boundary frames can be dismantled and results in the formation of a rigid structure (Pérez, et al., 2021). Hence, various materials are selectively employed in specific areas based on their distinct properties and corresponding roles, leading to dematerialization.

***Figure 3: Fabrication sequence of a fiber reinforced composite building element.***
*BUGA Fibre Pavilion / ICD/ITKE University of Stuttgart (2019, 09 May). ArchDaily. Accessed 08 Dec 2023.*
*<https://www.archdaily.com/916650/buga-fibre-pavilion-icd-itke-university-of-stuttgart> ISSN 0719-8884*

## 3.3 Modularity & Demountability

In this section the paper focuses on the fibrous elements created CFW on the aspects of modularity and demountability. The research questions formulated will help in understanding the design of the fibrous elements and how they are optimized to be modular and demountable while giving the designer form freedom. Additionally, the interrelationship between the structural assembly and the structural elements is discussed.

### 3.3.1 How can these structural and non-structural fibrous elements be combined in a modular and demountable way, while being thermally insulated, weatherproof and structurally optimized, to form fiber-based building systems?

To evaluate the structures made using CFW modularity needs to be defined. Modularity is used to describe various terms including standardization, customization and form freedom. The primarily difference between modularity and standardization is that modularity promotes flexibility and independence, standardization emphasizes uniformity and conformity (Miller & Elgård, 1998). They differ in their approach to design and implementation. CFW uses aspects of prefabrication and standardization, but due to the moldless approach a high customization (tailored) of the elements is made possible. According to Dr. Julian Fial, there are infinite number of variations of base components with the same production setup which makes this approach highly modular [See appendix 6]. The digital design and fabrication of CFW can therefore tailor specific parts to for example mechanical loads, showcased in the Buga Fibre Pavilion [See Appendix 4]. The constraints for the size of the building elements, according to Dr. Julian Fial, were mostly based on transport- and oven size and the reach of the robotic setup. As for tectonics, the elements created have an interrelationship between structure and artistic values. Due to its harmonious and systematic way of constructing it reflects the cultural and aesthetic qualities of the material, the structure and in that sense the architecture that is created (Stamenkovi, et al., 2020).

In 2021, the University of Stuttgart presented several pavilions [See Appendix 4] including the BUGA fibre pavilion which exhibited carbon fiber structures suitable for constructing large-scale spans (Pérez, Guo, & Knippers, 2022), Maison Fibre displaying a hybrid system of carbon fiber and LVL wood resulting in floor- and wall slabs and lastly, the LivMats pavilion demonstrating the use of flax fibers as an alternative to carbon- or glass fibers (Pérez, et al., 2022). They all had one particular thing in common, the interrelationship between the building- and element structures are important to take into account, as they influence each other. Lastly, as for the connections the remaining winding pins within the fibrous structure serve to establish a coupling between the beam elements that have been produced. The winding pin is attached to a metal hook plate using a bolt to be able to connect the element with the adjacent element. Hence, the anchor points of the elements play a vital role when making the connections and enables the convenient disassembly of the entire structure, leading to a significant degree of modularity and demountability.

FibR and the University of Stuttgart constructed and researched these structures separately and therefore an integration into a building system has not been designed and researched yet. According to Dr. Julian Fial [See appendix 6], the next phase for the company is to research and construct various building systems, which makes the current research all the more relevant. In the following paragraph these combinations have been researched through research-by-design and prototyping to achieve fiber-based building systems that are modular and demountable, while being thermally insulated, weatherproof and structurally optimized.

In the research by design phase [See appendix 7] various forms on a building level have been researched. This started firstly with the design of typical long span hangar typologies which feel from a designer's perspective odd and too sharp for the organically shaped structures using CFW. Secondly, a barrel typology is investigated which creates a more organic form language. Thirdly, the curvature of the elements has been expanded towards a connection on a support column in the middle in a single- and crossed span approach. Fourthly, various dome shapes have been explored which generate large spans with smaller elements. Lastly, a fibrous tree shaped column, illustrated in figure 4, has been designed. However, it needs to be noted that the curved shaped elements are harder to create with CFW due to its curvature. According to Dr. Julian Fial [See appendix 6] endless forms are possible using CFW on one condition that they can be wounded upon the robotic setup and can be demolded after curing.

***Figure 4: Fibrous tree column (Research-by-Design)***
*Steinfort, R.T. (2024)*

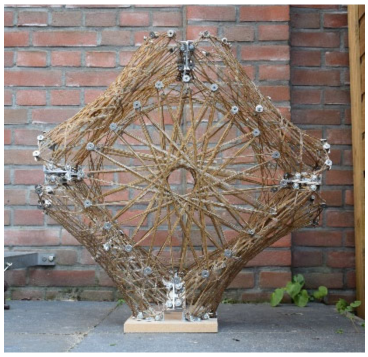

***Figure 5: Fiber-based building system (Prototyping)***
*Steinfort, R.T. (2024)*

The prototyping phase [See appendix 10] resulted in three types of beam- and four types of panel elements, one type of floor slab and two skin types being explored on a scale of approximately 1:20. The most important results were firstly that the winding syntaxes are crucial for the vitality of the creation of the elements itself and determines the fiber-to-fiber interaction and fiber orientation, which both have effects on the structural capacity of the elements to absorb the loads exerted on the structure. Additionally, the theories from Pérez, et al. (2021) on the optimal force exerted in axial compression were verified. The structure is flexible if forces were exerted perpendicular on the fibers and is stiff when forces are exerted parallel on the fibers [Appendix 10, figure 43, 44 and 45]. The elements can easily be disassembled due to the metal hook plate and bolt connection. However, the connections are not biobased and therefore an alternative needs to be found from other materials, such as wood. Additionally, the coreless characteristics of the beam [Appendix 10, figure 48] showcases the ability to thermally insulate the core and thereby enhancing the thermal capacity of the structure. The panel surfaces created were flexible, but shape-retaining. Hereby the edges of the panels were the most vulnerable which showcases the importance of creating stiff edges [Appendix 10, figure 52]. The panels could be connected on the structural fragment with various methods which all use the winding pins left in the structure. The combination of these beam and panel elements [Appendix 10, figure 56-57] illustrate the various possibilities of making integral fiber-based building systems. The floor slab [Appendix 10, figure 60] was found to be strong, but could not withstand the weight of a person (approximately 75kg). Lastly, the skin types [Appendix 10, figure 61] were tested on water repellency and showcased no moisture being impregnated in the fibers. Additionally, preliminary tests done by FibR [See Appendix 6] have shown that a flax fiber column exposed for 6 months to the elements still has similar structural capacities as when it was produced. However, it is too early to state if flax fibers can be used for the skin of the building system to shield the structure from the elements over a long period of time. In conclusion, as Dr. Julian Fial stated there is not one material that is perfect which suits all the characteristics you need structurally, thermally, biodegradability, flammability and for weather proofing.

### 3.3.2 How can computational design aid in creating fibrous structures that utilize dematerialization, are structurally optimized for the shapes needed for the program and enable form freedom?

The aesthetic, structural, and fabrication characteristics of fiber nets and fiber bodies in the design of fibrous structures created using CFW are difficult to understand. The complex interrelations between these characteristics are often too far removed from a designer's sense and intuition. Out of these design features, three hold the utmost significance: fiber-to-fiber interaction, fiber segment lengths, and fiber orientation. Hence, with artificial intelligence (AI), computational design can generate iterations by leveraging past simulations, a process referred to as form-finding, employing a fiber agent [See Appendix 5]. These designs generate the most optimal winding paths, therefore leading to the most efficient structures. Moreover, biomimicry is employed to comprehend the fibrous systems found in nature, which exhibit diverse arrangements and concentrations of fibers that adapt to the desired properties of the overall material structure. This approach maximizes the efficiency of the material and takes advantage of the local variability inherent in fibrous systems (Menges, Kannenberg, & Zechmeister, 2022). In addition, the same logic is applied as in load-bearing structures found in fiber composites in life forms, where the structure exhibits higher density along the lines of stress inside the structure. The merging of biomimicry, computational design, and AI in this computational approach leads to resource effectiveness and material efficiency. Lastly, computational design is also utilized for form finding the overall structure and determines the shape of the structural elements in the assembly, illustrated in figure 6. This showcases the interrelationship between assembly and the elements.

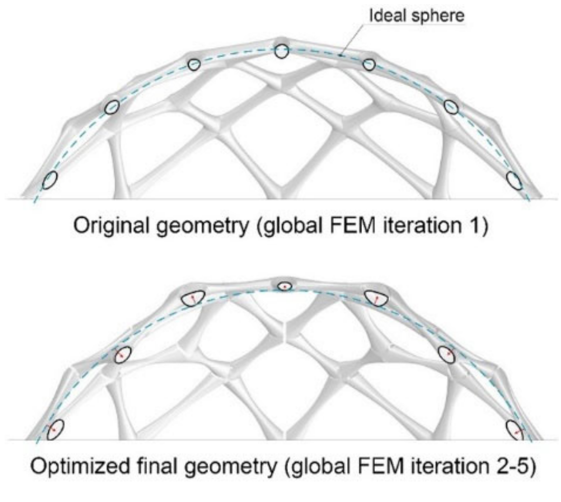


***Figure 6: Geometry optimization***
*BUGA Fibre Pavilion / ICD/ITKE University of Stuttgart (2019, 09 May). ArchDaily. Accessed 08 Dec 2023. <https://www.archdaily.com/916650/buga-fibre-pavilion-icd-itke-university-of-stuttgart> ISSN 0719-8884*

## IV. Discussion

Even though it was found that flax has great potential for using with coreless-filament winding, there are a few possible limitations to this current research. Firstly, the selected cases from the case study analysis only consisted of pavilions with limited temporally functions and, as a result, the potential effects of the fibrous structures made using CFW on a larger building scale could not be investigated. Secondly, prototyping was done by hand instead of using a robotic setup which could have influenced the end result of the fibrous structures on the aspects of structural capabilities. Thirdly, the interview conducted with Dr. Julian Fial, from FibR, can be slightly biased due to having interviewed the company that has invented coreless-filament winding in collaboration with the University of Stuttgart. Lastly, it is assumed that the skins produced during prototyping contained a significant quantity of epoxy resin, which presumably contributed to their water repellent properties and these findings are merely scientifically proven on long term effects.

Subsequent research should prioritize examining the connections among the fabricated fibrous elements in order to establish a completely biobased structure. Additionally, in this study the resin was not biobased and therefore further research should test the implications of using CFW with bio-resin on the structural and biodegradability aspects and therefore its feasibility in the building industry. Finally, additional research should incorporate interviews with various stakeholders in the field of coreless-filament winding to develop a more comprehensive analysis of the technique and its potential architectural applications.

## V. Conclusions

The material characteristics of flax makes it the most optimal natural fiber to use with coreless-filament winding due to its high cellulose ratio and length of the long fibers which gives the fibers their (tensile) strength. The level of lignin, pectin and hemicelluloses is optimal for the extraction of the long and short fibers and flax can he harvested locally in about 100 days. Flax fibers are predominantly optimal thermal insulators, but due to its material characteristics and the dematerialization approach result in flammable structures. Furthermore, flax fibers are in general biodegradable and hydrophilic which makes it not the most optimal weather proofing material. Nevertheless, these concerns can be mitigated by using resin treatment or alternative fiber based materials, such as basalt fibers, which are non-flammable. The construction of these lightweight structures using coreless-filament winding are fabricated using fiber filaments that are wound upon two boundary frames and impregnated with resin. In this process fiber-to-fiber interaction and orientation are the key factors that determine the structural abilities of the element. The fiber-based building systems constructed using CFW are modular due to form freedom and the flexibility in the production process. The various pavilions from the case study analysis have shown that long spans can be achieved with fibers, including flax fibers. Prototyping of various beams and panels have revealed that the connections are viable for demountability and that the elements can be thermally insulated to make the building system thermally sound. This proofs that fiber-based building systems can be viable with the combination of coreless-filament winding and locally harvested flax fiber. Although flax possesses favorable material properties for specific functions in the building system, it is not suitable for all of them. A combination of various elements made from different fiber types are therefore recommended to make use of the most optimal material characteristics.

The tailor made approach of CFW results in elements that have a high interrelationship between structure and artistic values which reflects the cultural and aesthetic qualities of the material. Additionally, this interrelationship is also visible between the elements and their specific function in the building and can therefore be defined as bespoke fibrous tectonics structures. The overall building- and element shape is endless with the condition that it can be wound upon the robotic setup and can be demolded. The combination of the form language created with the bespoke fibrous characteristics has the potential to develop a novel architectural language.

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