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Structural design challenges of bio-based composites and digital fabrication towards sustainable building systems

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Abstract

The combination of computational design, digital fabrication, and new materials in architecture is breaking with conventional ways of building and unveiling potential construction systems to reduce waste and pollution. Bio-based fiber-polymer composites bring the opportunity to replace conventional materials by creating lightweight structures that provide design flexibility and can reduce carbon footprint. However, they become nonstandard systems in which mechanical properties are highly uncertain and depend on factors related to the raw materials or their chosen fabrication technique. These emerging nonstandard structures do not fulfill building codes or design methods, requiring new approaches to prove their safety and reliability, and their design process needs to include a global vision of the entire life of the structure. This paper runs through a methodology for the integrative structural design of non-standard building systems combining a digital-physical and multi-scale design approach and elaborates on how this method can benefit from the circularity principles of narrowing, slowing, and closing the structure's resources loop. In particular, the paper showcases coreless filament wound bio-based composite structures as a case study to discuss their structural design challenges and reflect on the potential strategies to shorten the gap between research and industry, facilitating the realization of sustainable structures.

Keywords: structural design, digital fabrication, digital-physical workflow, multi-scale simulation, coreless filament winding (CFW), bio-based composite materials, sustainable structures, circular design.

1. Introduction

In pursuing sustainable development, the construction industry stands at a critical juncture, tasked with reimagining traditional methodologies to mitigate environmental impact while meeting the escalating global demand for infrastructure [1]. Central to this endeavor is the exploration of innovative materials and fabrication techniques that promise to revolutionize the landscape of structural design, breaking with traditional typologies [2]. Bio-based building materials constitute a promising frontier, offering a pathway toward resilient, resource-efficient structures [3].

Among them, the advent of bio-based composites derived from renewable sources, such as agricultural residues, natural fibers, and bio-polymers, presents a compelling alternative to conventional construction materials with significant carbon emissions [4]. Integrating these eco-friendly materials into structural frameworks can reduce construction projects' environmental footprint and foster a paradigm shift towards a circular economy, where waste is minimized and materials are reused or recycled. However, harnessing bio-based composites' full potential necessitates overcoming many structural design challenges [5]. These materials exhibit inconsistent mechanical properties, including variability in strength, stiffness, and durability, which demand meticulous consideration during the design phase. Moreover, moisture absorption, fire resistance, and long-term performance issues must be addressed to ensure bio-based composite structures' structural integrity and long-term behavior [6].

Digital fabrication technologies offer a transformative solution, enabling the precise modeling, customization, and fabrication of complex geometries with unparalleled efficiency and accuracy [7]. From computer-aided design (CAD) software to advanced robotic manufacturing processes, digital tools empower architects and engineers to push the boundaries of architectural expression. As a countereffect, structures made digitally usually present challenges for simulation and analysis methods [8], and novel structural design approaches are needed to integrate design, engineering, and fabrication, enabling not only the optimized design but also the proof of safety of the structure [9].

This paper aims to expose the intricate interaction between bio-based composites and digital fabrication in the realm of sustainable building systems. The paper uses robotically fabricated coreless filament wound fiber-polymer composite (FPC) structures to showcase and analyze the challenges of this design combination. The opportunities of this technique are explored through a set of reflections on how to address the described challenges and move towards the circularity principles of narrowing, slowing, and closing the structure's resources loop. This study seeks to inform and inspire engineers across the construction industry to embrace a holistic, environmentally conscious approach to building design and construction by delineating key principles, best practices, and future research directions.

2. Nonstandard building systems in the digitalization age

In the digitalization age, non-standard building systems are revolutionizing the construction industry by leveraging advancements in computational design processes, digital fabrication methods, and the utilization of unconventional materials [9]. These systems aim to create structures that are not only aesthetically innovative but also lighter, more sustainable, and higher performing than traditional building methods allow.

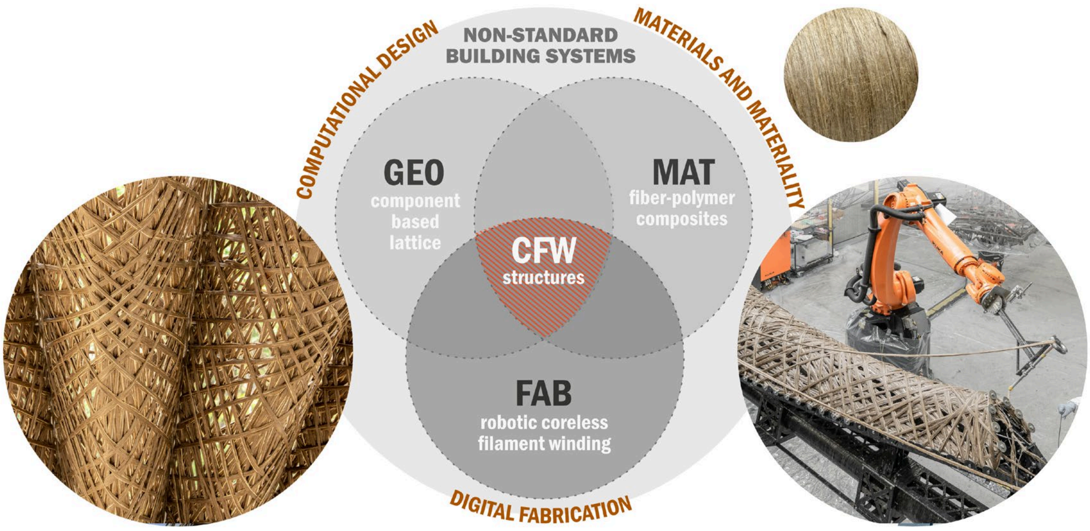

Figure 1: CFW bio-based fiber-polymer composites as an example of nonstandard systems (diagram: @M. Gil Pérez, photos: LivMatS Pavilion @ICD/ITKE/IntCDC University of Stuttgart)

Coreless filament-wound bio-based FPCs serve as a prime example of such non-standard systems (Figure 1). Enabled by the additive manufacturing technique of coreless filament winding (CFW), these structures achieve unprecedented levels of flexibility. CFW allows for the creation of larger components with intricate geometries while minimizing waste materials. However, the uncertainties coming from the bio-based material system present unique challenges for its design and manufacturing, involving the adaptation of design methods to the material requirements [10].

The robotic fabrication process of CFW involves the impregnation of fiber filaments through a resin bath guided by a planned robotic path [11]. The resulting lattice structure emerges by winding the fibers on discrete frames, offering lightweight solutions suitable for architectural applications [12]. Yet, predicting the mechanical properties of these structures remains complex and requires the utilization of alternative testing methodologies for its characterization [13], [14]. Besides, challenges also persist in ensuring their safety and feasibility, usually requiring the utilization of full-scale testing strategies [15]. Therefore, their design requires an integrative approach that combines computational design, simulation methods, and fabrication feedback in a digital-physical workflow [16].

In essence, non-standard building systems in the digitalization age signify a paradigm shift in the way we conceive, design, and construct buildings. By pushing the boundaries of traditional methods and embracing cutting-edge technologies, these systems offer boundless opportunities for architectural innovation while demanding innovative solutions to address the complexities they present in structural design and safety verification.

3. Integrative structural design of nonstandard building systems

Figure 2 shows an integrative structural design methodology for the design of building systems that cannot be design with standard procedures due to the lack of knowledge on the structural performance [9], [16]. The methodology provides a comprehensive framework for designing complex structures by integrating digital and physical realms along with architectural and structural considerations.

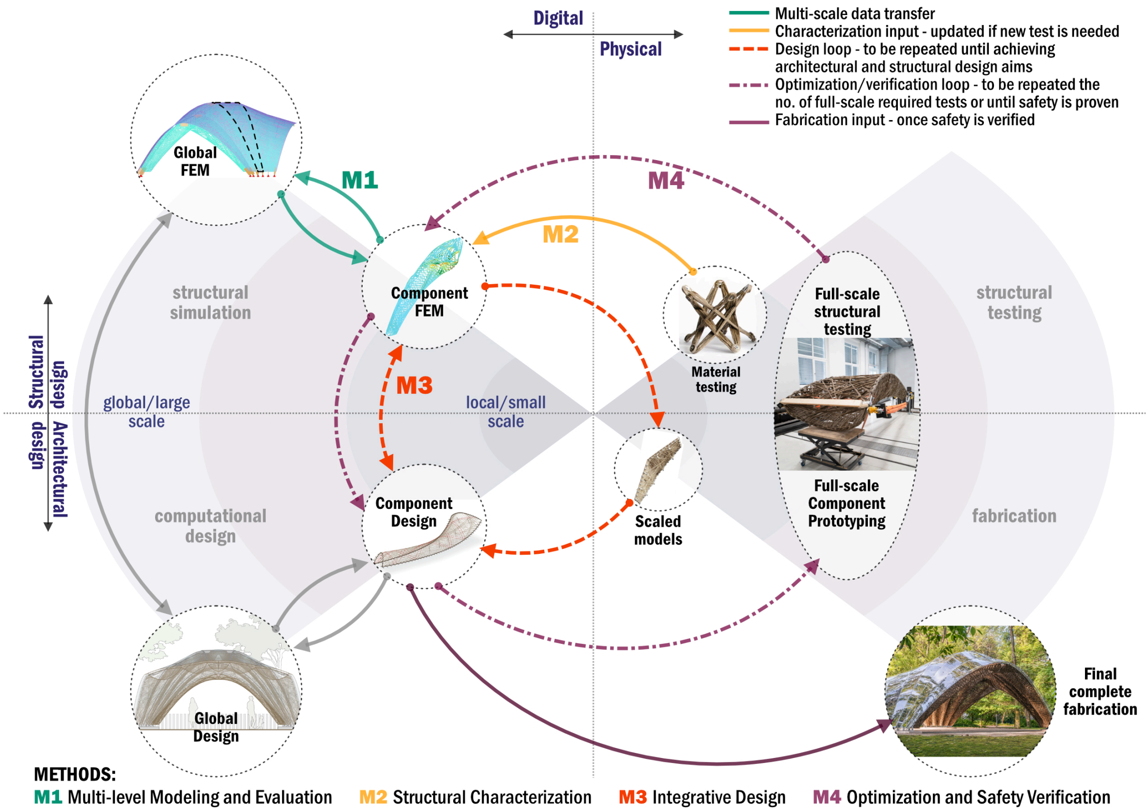

Figure 2: Integrative structural design of nonstandard building systems applied to CFW bio-based structures (diagram: @M. Gil Pérez, photos: LivMatS Pavilion @ICD/ITKE/IntCDC University of Stuttgart)

Figure 2 illustrates the design space for the framework divided into four quadrants: structural simulation, computational design, structural testing, and fabrication while incorporating a multi-scale approach. This framework is applicable to modular structures that allow for local-global discretization.

Overall, the integrative structural design methodology bridges the gap between digital simulations and physical testing, enabling the validation of innovative structures while ensuring safety and reliability. Through iterative processes and multidisciplinary collaboration, this methodology streamlines the design process and accelerates the adoption of new materials and fabrication techniques in the construction industry. The workflow encompasses four methodologies, marked in Figure 2 as M1 to

M4, and was demonstrated through the application to modular CFW structures like the BUGA Fibre Pavilion [15], [17], Maison Fibre [18], and LivMatS Pavilion [19], the last one being the first CFW structure built with a natural fiber material system.

- **Multi-level Modeling and Evaluation (M1):** This methodology involves a flexible Finite Element (FE) model approach, considering different refinement levels and perspectives to assess structures. This multi-level FE approach accommodates the evolving geometry and mechanical properties of CFW structures, updated through different calibration procedures, and allows for assessment from both global and component perspectives. This approach aids in early design stages, identifies misleading results, and saves modeling time.
- **Structural Characterization (M2):** Customized testing methods are essential to characterize unconventional fabrication techniques and material systems, ensuring reliability and informing the design process. M2 involves customized testing methods to characterize CFW structures, considering factors like fabrication parameters, geometry, fiber volume ratio, and compaction. Small-scale prototypes and destructive testing inform the design and help calibrate FE models.
- **Integrative Design (M3):** This methodology emphasizes a digital design workflow incorporating iterative structural feedback, multidisciplinary collaboration, and a digital-physical design loop to optimize form, geometry, and material usage. M3 focuses on the design of the components, emphasizing iterative structural feedback and the physical feedback from models and prototypes to calibrate the design and reduce uncertainties in the simulations.
- **Optimization and Safety Verification (M4):** Given the lack of standardized methods for new materials and fabrication systems, this methodology stresses the importance of full-scale destructive testing to validate structural safety and reliability. It involves iterative testing schemes to calibrate the FE models. M4 emphasizes utilizing modular full-scale destructive testing of a representative component to validate the complete structure, proving structural safety and reliability. There is also room for structural optimization through the iterative testing scheme.

4. Key aspects for the sustainable structural design of bio-based FPC structures

The methodology described above has been proven successful by realizing full-scale demonstrators, such as the LivMatS Pavilion [19]. Therefore, it is possible to design and verify the safety of nonstandard systems with materials not covered by conventional codes. However, relying on full-scale testing can sometimes be time-consuming and costly, and to achieve sustainable systems, the design process needs to include a global vision of the entire life of the structure. In addition, the uncertainties brought by a bio-based material system amplifies the design challenges of the structure.

Section 4.1 looks at the structural design challenges encountered in the realization of CFW bio-based FPC. In contrast, section 4.2 explores the strategies necessary to confront these challenges and move towards more sustainable structures.

4.1. Structural design challenges

Developing bio-based FPC fabricated through CFW presents a promising avenue for sustainable manufacturing. However, several structural challenges arise from using bio-based material systems and digital fabrication techniques. These challenges primarily revolve around the following key aspects: reliability of the supply chain, compatibility of the fiber-matrix interface, thermal stability within the processing temperature range, consistency quality and variability of mechanical properties, characterization and scalability of these properties, long-term durability against moisture, temperature variations, and UV exposure, and in addition, difficulties in the assessment of sustainability.

4.1.1. Material and fabrication

The supply chain presents one of the first challenges to consider, as the availability of bio-based fibers and polymers may be less established or reliable compared to conventional materials. Establishing a robust and continuous supply chain for bio-based materials is crucial to ensure uninterrupted production.

On the composite level, the compatibility at the fiber-matrix interface stands out as a critical issue. Ensuring strong adhesion between the bio-based fibers and the polymer matrix is essential for optimal mechanical properties. Unlike synthetic fibers, bio-based fibers may exhibit variations in surface properties, which can affect the bonding with the polymer matrix. This challenge is exponentiated due to the fabrication technique. In CFW, the robot cannot provide sufficient pressure to ensure compaction, and the impregnation process was designed for its use with synthetic fibers. Figure 3 compares the cross-section of a carbon fiber specimen with two flax fibers from a previous research project [19]. Even though picture A presents voids characterized by the lack of compaction during the CFW process, in picture B, it is possible to see voids and fully dry areas showing a lack of impregnation in the flax specimen. Picture C shows the improvements in material impregnation after several iterations of adaptations to the robotic setup.

Figure 3: Comparison of the cross-section of carbon (A) and flax fiber filament-wound composite (B hand-wound, C robotically wound after setup improvements) [19]

Thermal stability poses another significant challenge, particularly regarding the processing temperature range. Many bio-based fibers and polymers have lower thermal stability compared to their synthetic counterparts. This limitation imposes constraints on the selection of processing parameters during robotic filament winding and during the curing process.

4.1.2. System characterization and design

Maintaining consistent quality and uniform properties across bio-based FPCs is also challenging, intensified by difficulties in characterization and scaling results to large-scale applications. Natural fibers present variations in material composition, fiber geometry, and processing parameters that can lead to non-uniform mechanical properties and structural integrity in comparison with synthetic fibers. Figure 4 compares carbon and flax fibers for plate-like specimens (Figure 5B) under bending. The scattering of the results of the flax specimens is shown in the right graph. It can also be observed that the elastic behavior of the flax specimen is almost non-existent compared to carbon.

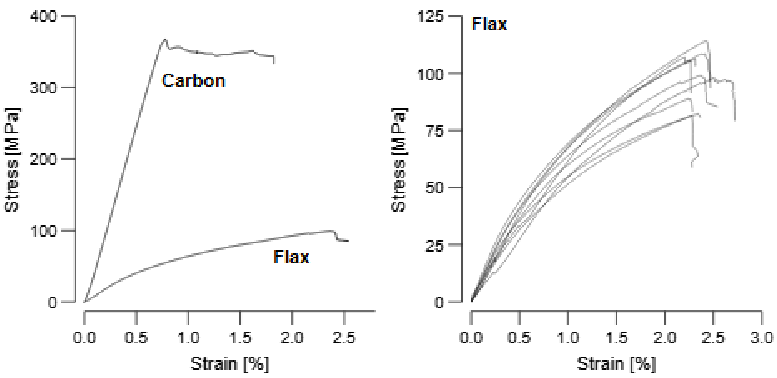

Figure 4: Comparison of the structural behavior of carbon and flax fiber filament-wound specimens under bending [20] (test setup B in Figure 5)

Besides, transferring laboratory-scale findings to industrial production settings introduces additional complexities and requires the consideration of fabrication parameters. There have been numerous attempts to test and characterize CFW structures (Figure 5), but none of them can represent and predict the actual behavior of large-scale structures. Therefore, they are only used for partial calibration of the models, or as a design guidance.

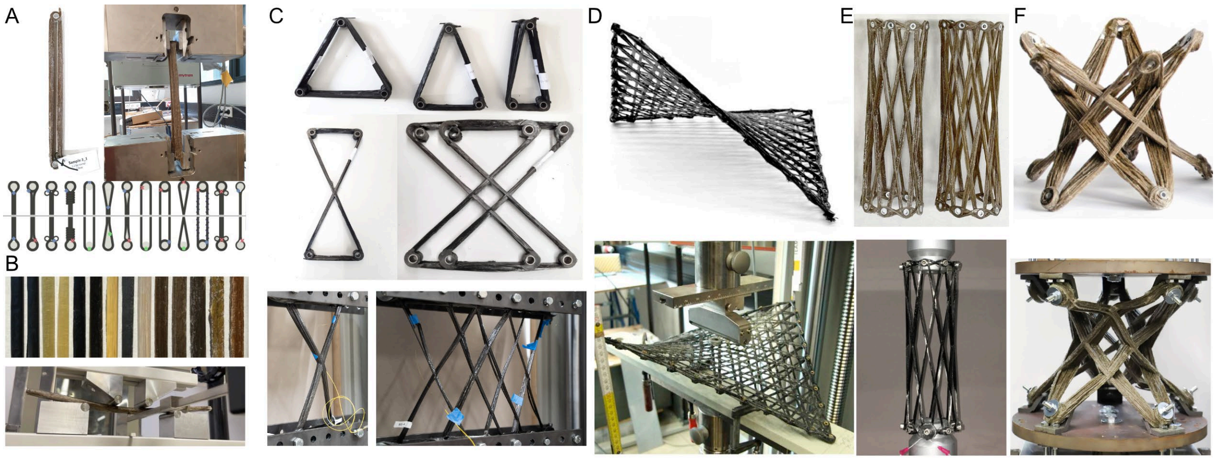

Figure 5: Overview of structural testing specimens utilized to characterize CFW structures: A: loop specimen [19], [21], B: plate-like specimen [20], C: simple triangle or cross specimen [22], [23], D: lattice specimen [24], E: tubular specimen [20], [25], F: star specimen [13], [19].

The design of these types of structures requires the collaboration and integration of various disciplines and domains [23]. While this interdisciplinary approach has been effectively implemented in research settings, its practical utilization in real-world applications remains challenging. One of the primary hurdles lies in the exchange, analysis, and evaluation of data across different disciplines to effectively influence the design optimization of these structures.

4.1.3 Long-term behavior

Ensuring long-term durability presents multifaceted challenges, including resistance to moisture, temperature fluctuations, and UV radiation. Bio-based FPC materials may exhibit different degradation mechanisms than synthetic ones, requiring thorough characterization and testing under relevant environmental conditions. Protective coatings or additives may be necessary to enhance durability and extend the service life of bio-based composite structures.

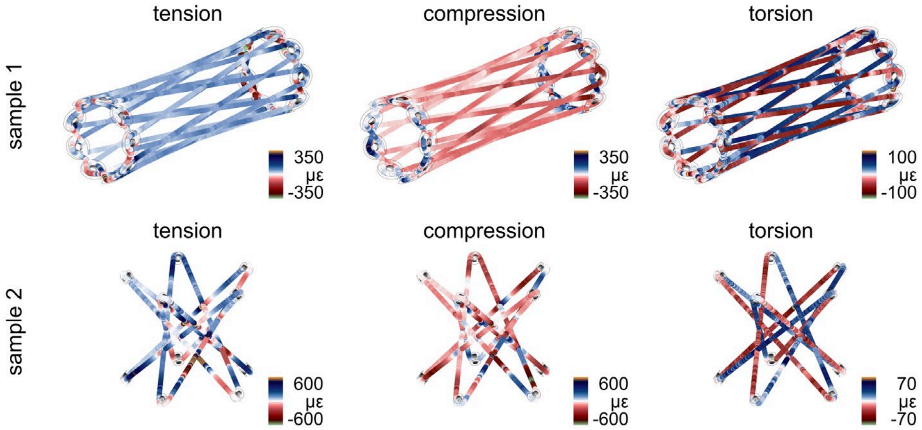

Figure 6: Implementation of fiber optical sensors in CFW structures [25].

Implementing fiber optical sensors in CFW has been one of the strategies to monitor the behavior without the need for full-scale testing (Figure 6) [25]. This strategy remains challenging due to the difficulties in the interpretation and postprocessing of the strain data, which are highly influenced by the sensor's location embedded in the fiber bundle and the forces and bending moments within the structure. This influence is recognizable when comparing the tube (sample 1) and star (sample 2) specimens in Figure 6. The tube specimen, being simpler and more regular in shape, captures loadings such as tension and compression with precision. However, the star specimen shows a positive and negative strain distribution in all loading situations, making it harder for interpretation.

4.1.4 Life cycle analysis (LCA)

In addition to the structural challenges, conducting a comprehensive life cycle assessment (LCA) for bio-based FPCs is hindered by the limited data availability. LCA plays a crucial role in evaluating the environmental impact of materials and processes throughout their entire life cycle, from raw material extraction to end-of-life disposal. Most of the current studies for CFW structures only considered the processing of the materials for the comparison of embodied energy and global warming potential (GWP) [19], [20].

Without specific information from the resin and fiber providers, the only possible approach is to compare the materials with data available in the literature. However, this data scatters greatly. For example, the embodied energy per kg of material found in the literature for flax fibers ranges between 6.5 [26] to 86 [27] MJ/kg, while GPW is between 0.44 [28] to 0.9 [29] CO2-eq./kg. On top of this, the final sustainability indexes should be calculated, considering the resulting composite's fiber volume ratio and the actual structural capacity as shown in Figure 7. To compare different materials, such as carbon and flax fibers, the structural capacity should be considered by assuming the required material to withstand the same loading condition. In practice, it can be seen that the resin contribution in the calculation of these indexes tends to be the detrimental factor when considering sustainability.

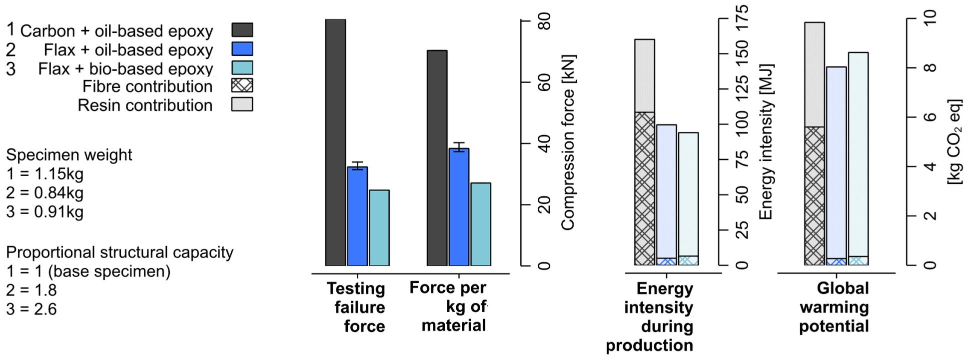

Figure 7: Comparison of LCA indexes calculated for carbon and flax specimens (specimen F in Figure 5) [19].

Due to all these parameters, the studies are so far not generalizable, and a more robust methodology to assess sustainability in early-stage applications that account for this lack of data is needed. Addressing this data gap is essential for making informed decisions regarding the environmental sustainability of bio-based FPC materials and guiding the development of eco-friendly manufacturing practices.

4.2. Research outlook

To address the structural design challenges associated with bio-based FPCs and digital fabrication techniques, innovative solutions are required across various fronts. Building upon the integrative structural design methodology described in Figure 2, the next research step is to extend the methods following the circularity principles of narrowing, slowing, and closing the structure's resources loop, directly translated into the strategies of "use less", "use longer", and "use again". Figure 8 shows an overview of the key points that can enable the application of bio-based FPCs as building systems.

Firstly, in tackling material selection and fabrication challenges, it is important to assess the reliability and availability of bio-based fibers and polymers for structural applications and establish a robust supply chain and data-gathering approach. Collaborating closely with suppliers to ensure consistent quality and availability can help mitigate production interruptions and improve the material's characterization and performance knowledge. Moreover, adjusting advanced fabrication techniques that cater specifically to the unique properties of bio-based fibers is essential. Enhanced impregnation processes and optimized robotic setups can improve adhesion at the fiber-matrix interface, ensuring optimal mechanical properties.

Incorporating feedback from life cycle assessments is integral to sustainable structural design. This includes evaluating the environmental impact of material selection and fabrication techniques, considering factors such as energy consumption, greenhouse gas emissions, and resource depletion. By integrating LCA feedback into the design process, designers can make informed decisions to minimize the environmental footprint of bio-based composite structures. Attention should be given to how to deal with the lack of data, and still be able to give guidance on the potential sustainability index of the system to be designed.

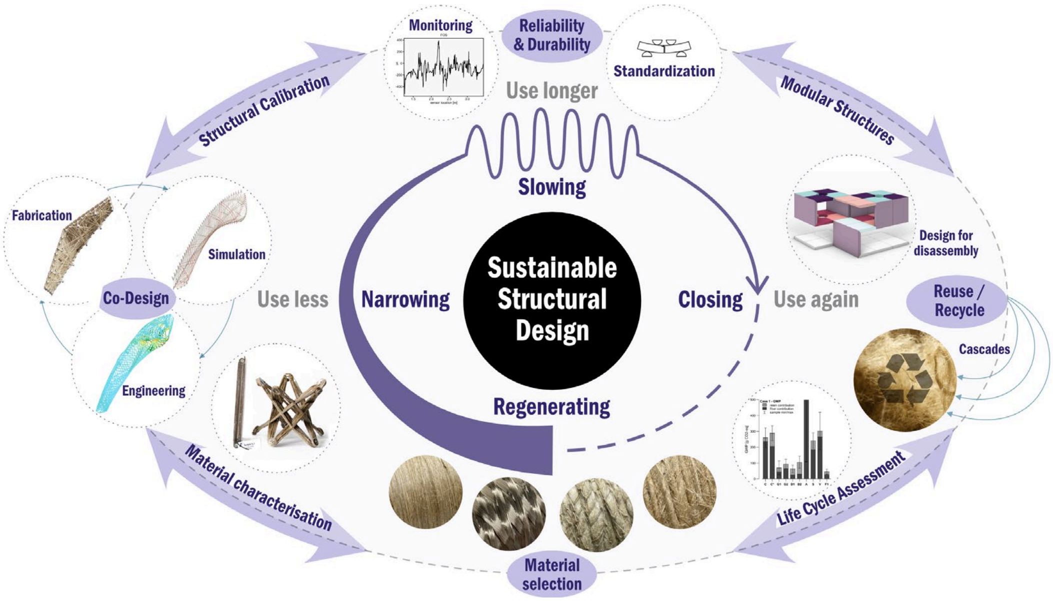

Figure 8: Challenges and extension of the methods following the principles of circularity

In terms of computational design development, integrating structural design, simulation, and fabrication feedback has been proven to be a promising solution. This co-design strategy enables more accurate predictions of structural behavior, leading to more efficient designs and reduced environmental impact. Also, in this case, the methods should pay attention to data handling, processing, and analysis, as well as account for uncertainties during the simulation processes. In addition, improving simulation and characterization capabilities is essential for accurate structural design. This involves developing computational models that capture the behavior of bio-based materials under various loading conditions and environmental factors. By refining simulation techniques to account for material variability and processing constraints, the reliability of structural predictions can be enhanced.

The implementation of monitoring and standardization methods is proposed to address challenges related to long-term behavior and performance uncertainties or lack of data. This involves integrating sensor technology to monitor structural performance in real time and implementing standardized quality control and calibration protocols. The standardization of bio-based structural systems requires leveraging structural data to inform the development of industry standards. By gathering data on material properties, performance metrics, and structural behavior, designers can contribute to the extension of structural codes and guidelines. This can facilitate the adoption of bio-based materials in mainstream structural engineering practice and ensures the consistency and reliability of structural designs.

Reuse and recycling strategies play a crucial role in promoting sustainability throughout the product lifecycle. Designing modular structures for disassembly facilitates easy reuse of components, prolonging the lifespan of materials and reducing waste. Additionally, exploring cascading strategies where materials are recycled and repurposed further maximizes resource efficiency. Early consideration of reuse and recycling principles in the design phase ensures that these strategies are seamlessly integrated into the product lifecycle. By addressing data gaps and developing robust methodologies for sustainability assessment, designers can make informed decisions that drive the adoption of eco-friendly manufacturing practices.

5. Conclusion

Bio-based FPCs bring the opportunity to replace other conventional materials, providing design flexibility, lightweight structures, and reduced CO2 emissions. However, their mechanical properties are highly uncertain and depend on factors related to the raw materials (such as defects in the fibers and impregnability) or their chosen fabrication technique. To address these issues, this paper proposes the extension of an integrative structural design methodology towards the consideration of circularity principles.

Addressing the structural challenges inherited from a bio-based material system requires interdisciplinary collaboration between disciplines such as architecture, structural engineering, materials science, computer science, robotics, and supply chain experts. By overcoming these obstacles, bio-based FPCs fabricated robotically through CFW hold immense potential for sustainable manufacturing across various industries. This research will allow the transformation of a material-efficiency strategy into a complete eco-effectiveness approach, enabling the design of sustainable structural systems with bio-based materials.

Acknowledgments

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