MECHANICALLY-INFORMED COMPUTATIONAL FORM-FINDING FOR BIOBASED MATERIALS IN THE CASE OF BACTERIAL CELLULOSE

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ETHICAL DECLARATION

I hereby declare that I am the sole author of this thesis and that I have conducted my work in accordance with academic rules and ethical behavior at every stage from the planning of the thesis to its defense. I confirm that I have cited all ideas, information and findings that are not specific to my study, as required by the code of ethical behavior, and that all statements not cited are my own.

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27 December 2022

ABSTRACT

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Recent studies in digital design and fabrication processes focus on the potential of using biological systems in nature as mathematical models or, more recently, as biobased materials and composites in various applications. The reciprocal integration between mechanical and digital media for designing and manufacturing biobased products is still open to development. The current computational form-finding scripts involve an extensive material list that can be enhanced by extending with biobased materials. This dissertation explores a customized form-finding process by suggesting a framework through mechanically-informed material-based computation. Bacterial cellulose, an unconventional yet potential material for design, was explored across its biological growth, tensile properties, and the integration of datasets into computational form-finding. The initial results of the comparison between computational form-finding versus mechanically-informed computational form-finding revealed a difference in terms of both the resulting optimum geometry and the maximum axial forces that the geometry could actually handle. Although this integration is relatively novel in the literature, the proposed methodology has proven effective for enhancing the form-finding process within digital design and fabrication and bringing us closer to real-life applications. This approach allows conventional and limited material lists in various computational form-finding scripts to cover novel biobased materials once the quantitative mechanical properties are obtained. This method contributes to design science, material science, architecture, and a sustainable future against the ever-growing effects of the Anthropocene.

Keywords: Computational form-finding, structural performance, tensile test, bacterial cellulose.

ÖZET

BAKTERİYEL SELÜLOZ ÖZELİNDE BİYOLOJİK TABANLI MALZEMELER İÇİN MEKANİK OLARAK BİLGİLENDİRİLMİŞ HESAPLAMALI FORM BULMA

Turhan**,** Gözde Damla

Tasarım Çalışmaları Doktora Programı

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Hesaplamalı tasarım ve üretim süreçlerindeki son çalışmalar, doğadaki biyolojik sistemleri matematiksel modeller olarak veya çeşitli uygulamalarda biyolojik tabanlı malzemeler ve kompozitler olarak kullanma potansiyellerine odaklanmaktadır. Biyolojik tabanlı ürünlerin tasarlanması ve üretilmesi için mekanik ve dijital medya arasındaki karşılıklı entegrasyon hala geliştirilmeye açıktır. Mevcut hesaplamalı form bulma betikleri, kapsamlı bir malzeme listesi içermesine rağmen biyolojik tabanlı malzemelerin bu listeye eklenmesiyle daha da geliştirilebilir. Bu tez, mekanik olarak bilgilendirilmiş malzeme tabanlı hesaplama yoluyla bir çerçeve önererek özelleştirilmiş bir form bulma sürecini araştırmaktadır. Pek alışılmadık ancak tasarım için potansiyel bir malzeme olan bakteriyel selülozun biyolojik büyüme süreci, mekanik malzeme özelliklerinin elde edilmesi ve bu veri setlerinin hesaplamalı form bulma sürecine entegrasyonu incelenmiştir. Standart hesaplamalı form bulma ve mekanik olarak bilgilendirilmiş hesaplamalı form bulma arasındaki karşılaştırmanın sonuçları, hem elde edilen optimum geometrinin formu hem de geometrinin gerçekte kaldırabileceği maksimum eksenel kuvvetler açısından büyük bir fark ortaya çıkarmıştır. Bu entegrasyon literatürde nispeten yeni olmasına rağmen, önerilen yöntemin hesaplamalı tasarım ve üretimdeki yapısal form bulma sürecini geliştirmek ve pratiğe yaklaştırmak için etkili olduğu gözlemlenmiştir. Bu yaklaşım, nicel mekanik özellikler elde edildikten sonra yeni malzemeleri kapsayacak şekilde çeşitli form bulma ve yapısal optimizasyon betiklerindeki geleneksel ve sınırlı malzeme listelerinin genişletilmesine izin vermektedir. Bu yöntem, tasarım bilimine, malzeme bilimine, mimarlığa ve Antroposenin sürekli artan etkilerine karşı sürdürülebilir bir geleceğe katkıda bulunur.

Anahtar Kelimeler: Hesaplamalı form bulma, yapısal performans, gerilme testi, bakteriyel selüloz.

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CHAPTER 1: INTRODUCTION

Domination of form and function over the nature of materials is one of the reflections of Modernism; however, today, within the context of modern design and production approaches, the detached process of form-making from material knowledge has transformed away (Sennet, 2008). In parallel to Modernism, mass production, in other words, producing low-cost and repetitive components emerged as the result of the Industrial Revolution (Jencks, 1984). Afterward, by the digital revolution, the explorations in the knowledge of computer-aided design (CAD) have led to a reinforcement of a non-material approach to design and automation in construction. Once the form was liberated from its physical presence, the digital design spaces enhanced the formal expressions; however, the gap between form and materiality was widened more; therefore, the distinction between modeling, analysis, and fabrication became visible (Oxman, 2007).

In parallel with CAD technology, digital design spaces enabled designers and architects to generate creative, complex geometries. Free form has become a phenomenon addressing mass customization instead of mass production. At this point, the question of materiality has become one of the primary concerns in architecture and architectural theory, both in terms of style and expression and as a philosophical issue concerning the different roles and impacts of built form. Therefore, the material has become a tool not only for questioning and criticizing but also for exploring the potential of the relationship of form, function, structure, and materiality. Increasing interest in the potential of emerging technologies has led to inquiries into innovative material use, followed by explorations into biobased materials and composites (McQuaid and Beesley, 2005). Therefore, the new era of explorations through digital media in design fields appeared as “Material-based design computation” first coined by Oxman (2010).

Form-finding processes, including material behavior studies, which actually date back to the 1970s, have become a focus again in design studies (Otto and Glaeser, 1972; Otto et al., 1990; Otto and Rasch, 1995; Otto and Nerdinger, 2005). Developments in biology and material sciences started to be considered as fundamental sources for advanced material design (Thom, 1975; Ruse and Hull, 1989; Paton, 1992; Goodwin, 1994; Kauffman, 2000; Kumar and Bentley, 2003; Forbes, 2004; Bar-Cohen, 2006). The growing interest of designers in the development of biological and morphological structures has brought about a new materiality approach based on organic, biodegradable, renewable, and recyclable materials to be used in a composite form or without any reinforcements.

Moreover, since biotechnology can address most of the environmental problems caused by the technological advancements that occurred in previous years, it has given a chance to designers to design man-made functions out of biological functions. The programmability of DNA, constructing digital libraries, and designing new tools have allowed designers to utilize biology in design processes for a better future.

When contemporary examples are investigated, it is observed that biobased materials that are being grown enable designers to design and fabricate more environmentally friendly and biodegradable products. However, some lose the biological benefits of living matter, such as the capability to heal against external damage after the growth process. For example, mycelium, a type of mushroom found on the surface of wood chips, is being utilized to heal the damages together with other bacteria; however, they lose their ability to grow up to a certain point. On the other hand, there are examples of bacteria used in materials science to convert energy into fuels. For instance, some bacteria produce silk fibers or biofuels, which can transform solar energy and regulate carbon dioxide levels in the air. Contrary to the self-healing type of material studies, living matters act as active materials which are constantly adaptive and responsive to environmental conditions. This material design approach could potentially contribute to the ecological cycle while gaining ground for design practices. This approach does not damage the ecology; instead, it improves the life cycle.

Therefore, in this dissertation, an integrated methodology for mechanically-informed computational form-finding for biobased materials is proposed to investigate sustainable structures at different design scales further. To demonstrate that, this dissertation experiments with a frequently explored biobased material recently, bacterial cellulose, for structural use, as a case study. The process emphasizes transforming a specific biological material into a structural material with promising material properties and structural capabilities.

By constructing the foundations onto a new materiality approach that prioritizes the material itself first, rather than following the idea of form follows function, this study adopts an experimental process of biobased material computation. This integrated framework anticipates bringing together a number of methodologies from different disciplines, such as mechanical engineering, bioengineering, and computational design, at the intersection where design literally meets living matter. The aim here is to show how different design prototypes can potentially shape our relationship with biology in new ways in design; change the design process, augment the quality of ideas and outcomes; thus, question the perception of making spaces for living.

1.2. Aim and objectives

The aim of this dissertation is to enhance the computational form-finding process for biobased materials that do not have fixed and established material properties such as maximum tensile strength, stress, or strain, to transform a specific biobased material into a structural material at all scales. In this dissertation, bacterial cellulose and plant cellulose fibers are considered as a composite that is potentially applicable for building components or industrial products through the new materiality approach based on organic, degradable, renewable, and recyclable materials. In this manner, an integrated framework is proposed to highlight the necessity for a holistic approach towards the computational form-finding of biobased materials and composites that are relatively novel for structural applications.

The main objectives to achieve the above aim are as follows:

- Defining the existing methods and tools of form-finding
- Observing the nature of bacterial cellulose and making modifications to increase the exponential growth of bacteria cells
- Measuring material properties
- Designing a self-standing reversed catenary geometry informed by mechanical test results

1.3. Research questions

In order to enlarge the amount of available material data in the form-finding processes, the aim is to create a framework for biobased composite materials and complex geometries. In order to do so, the following questions are asked:

1. How accurately do the computational form-finding methods and tools reflect on physical applications with currently available processes?
2. How can the material properties be introduced into computational form-finding processes in order to achieve accuracy?
3. How can computational form-finding processes be enhanced to work with complex geometries realized with biobased materials and composites?
4. How can the material properties of biobased materials and composites be measured and integrated into computational form-finding methods and tools?

1.4. Methodology

The methodology of the dissertation is based on quantitative data where the systematic approach is divided into three main stages: *Acetobacter Xylinum (A. xylinum)* growth and composite material design; measuring material properties through tensile testing; and mechanically-informed digital form-finding. The chapters are organized accordingly (Figure 1).

Following the introduction and definition of terms in Chapter 1, a background literature on form-finding is provided to show different approaches and classifications of methods and tools. The computational methods and tools for form-finding are classified according to the specific goals of the optimization process. Since the aim of this dissertation is to integrate the material properties of biobased materials, in particular, another classification is introduced for biobased materials. The design process of nature is also reviewed by giving examples from natural growth mechanisms and shared principles of biology, and computational design is discussed. Then an integrative framework is proposed to elaborate on the potentials and to review the distinctive aspects of biobased materials that are not assembled but instead grown. The reviews on the design and fabrication strategies that have been developed by the fusion of multiple disciplines are conducted. Later, bacterial cellulose, its material properties, and its behavior under different environmental conditions are discussed. Then, industrial applications for further exploring the literature for multiscale applications are discussed. Lastly, several experiments are conducted to study the nature of bacterial cellulose in a laboratory environment through mechanical tests on the material properties. At the end of a series of experiments and testing, the results are outlined by observing the behavior and properties of bacterial cellulose biofilms.

Finally, the mechanical test results are incorporated into a generic computational form-finding process by exploring the operation of Kangaroo Physics plug-in on Grasshopper through series of experiments. The results are discussed and the future studies are given at the end of the dissertation.

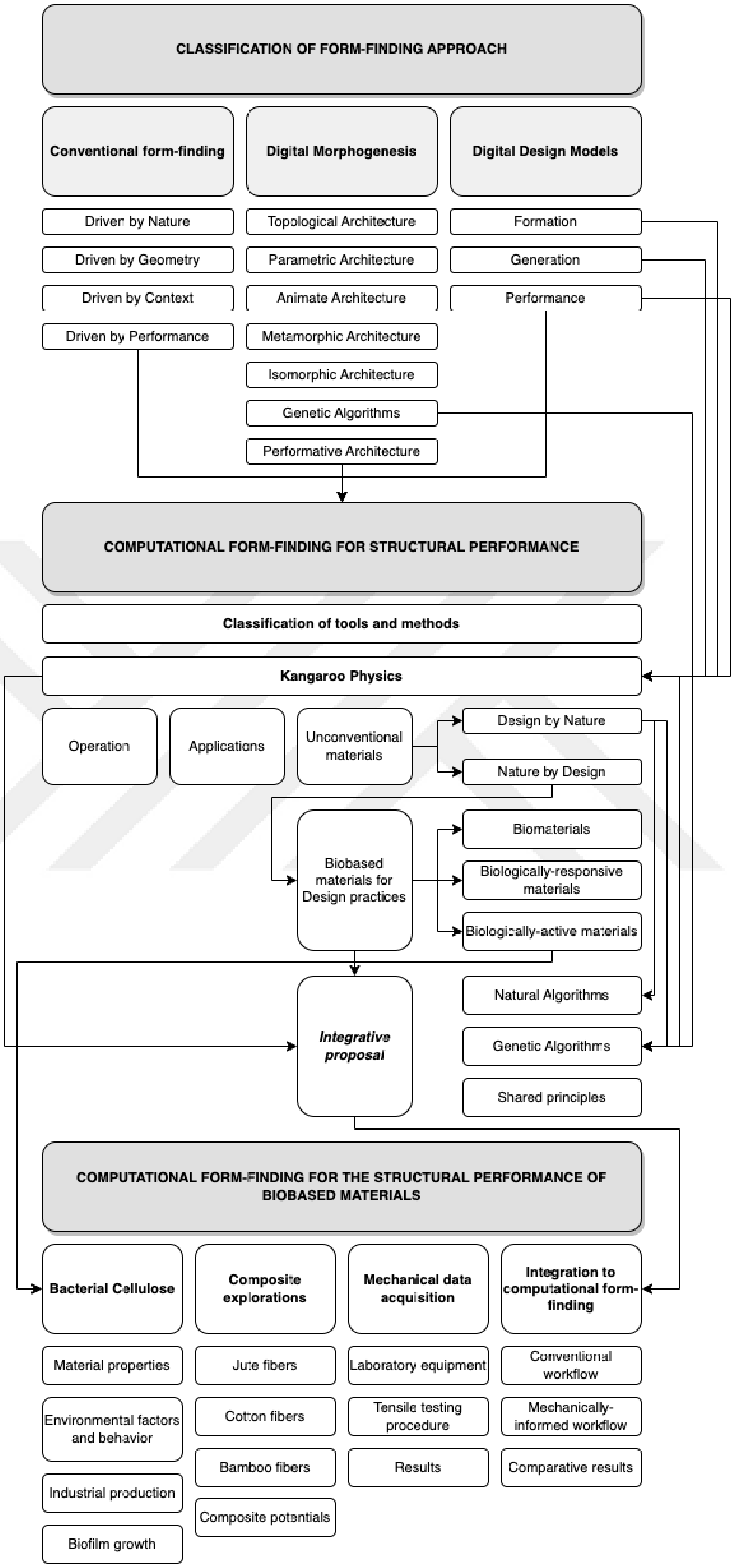

Figure 1. Methodology of the dissertation

In the same section, digital and mechanically-informed workflow with their methodologies, applications, and results are discussed in depth with technical details. In the digital workflow, a catenary geometry is explored, optimized, and the results are analyzed. In the mechanically-informed workflow, tensile testing results regarding bacterial cellulose-based composite biofilms are obtained to be integrated back into the digital workflow. The computational form-finding process is then conducted with the aid of the tensile testing results. This chapter is experimental in such a way that it presents results in both computational and mechanical processes.

In the conclusion, the fusion of interdisciplinary methods and interdisciplinary culture of the proposed form-finding process is discussed, followed by the highlights of the specific contributions of this experimental material study process, and putting forward potential future works getting off the ground in relation to these experiments.

1.5. Limitations

The limitations have two facets as follows:

- The lack of literature on bacterial cellulose as a structural material:

The use of biobased materials and composites as a structural material is a rather developing field of research, although there is a growing number of examples of such materials manufactured through molding or free-grown. However, a systematic mechanical exploration for structural evaluation needs further exploration to establish a common framework, methods, and tools.

- The lack of a library in computational form-finding tools on the properties of biobased materials to compare results:

The current computational form-finding tools have a limited list of materials, therefore, it is challenging to introduce the exact material properties and to have an accurate form-finding result in real-life applications. First, there is a need to obtain the mechanical properties of such materials and then integrate these properties into computational form-finding methods and tools. Moreover, the results of such integrative methods cannot be compared with the existing literature but could become the first step for further explorations.

Despite all limitations, the study suggests a novel combination of multidisciplinary methods and is expected to enlighten the process of utilizing biobased materials in computational design and digital fabrication by incorporating specific material properties into the process of form-finding.

CHAPTER 2: LITERATURE REVIEW ON THE CLASSIFICATION OF FORM-FINDING APPROACHES IN ARCHITECTURE

This chapter provides an overview of the different approaches to form-finding in architecture that have been used in practice and research. This includes a brief description of the key characteristics and features of each approach, as well as examples of how they have been applied in different contexts. The chapter provides a critical analysis and comparison of the different form-finding approaches, highlighting their strengths and limitations.

2.1. An overview of form-finding approaches in architecture

Form-finding refers to the process of exploring and generating the form of a structure or design (Chilton, 2012; Belanger, 2017; Kuo, Cheng and Tsou, 2021). There are various approaches to form-finding in architecture, which can be classified based on their underlying principles, techniques, and tools (Cuff, 2011; Nash, 2018; Nash, 2021). Form-finding, or the process of determining the optimal geometry of a structure to self-support a given set of loads, can be approached based on several classifications found in the literature (Table 1).

Table 1. Form-finding classifications based on the literature

CLASSIFICATION	FORM - FINDING CLASS	FIRST USES	PRIORITIES	PIONEERS ADOPTING THE APPROACH	EXAMPLES FROM RESEARCH AND PRACTICE
PHYSICAL FORM-FINDING	**Driven by Nature**	Antoni Gaudi (1883), Christopher Alexander (1977)	Natural processes, organisms or phenomena	Antoni Gaudi, Santiago Calatrava, Frank Gehry	Sydney Opera House (Jørn Utzon, 1973), Guggenheim Museum (Gehry, 1997)

Table 1 (continued)

	Driven by Geometry	Euclid and Pythagoras, Leonardo Da Vinci	Geometric shapes or patterns	Le Corbusier , Mies van der Rohe	Villa Savoye (Corbusier, 1929), Farnsworth House (van der Rohe, 1951)
	Driven by Context	Contextualistsuch as Peter Smithson (Smithson, 1956); Frank Lloyd Wright (Wright, 1943)	Local culture, climate, or site conditions	Tadao Ando, Frank Lloyd Wright	Church of the Light (Ando, 1989), Fallingwater (Wright, 1935)
	Driven by Performance	Structuralistsuch as Ove Arup (Arup, 1970) and Félix Candela (Candela, 1964)	Structural, thermal, or acoustic performance requirements	Arup, Norman Foster, Zaha Hadid	Hearst Tower (Foster, 2006), Guangzhou Opera House (Hadid, 2010)
DIGITAL DESIGN MODELS	**Formation-based models**	Kostas Terzidis (Terzidis 2003)	Form-finding as a type of event, rather than a sequence of static frames	Architects specializing in animation and parametric design, both of which heavily rely on topology	“Algorithms for Visual Design Using the Processing Language” Terzidis, K. (2003); “Digitally fabricated architecture” (Hansmeyer and Dillenburger, 2012)
	Generation-based models	George Stiny (Stiny, 1980)	Inclusion of mathematical mechanisms for generative processes such as evolutionary models and shape grammars	Michael W. Mahoney "Evolutionary Design by Computers", Peter Testa “Swarm intelligence”	"Introduction to Shape and Shape Grammars" (Stiny, 1980); “Responsive architecture" (Weinstock, 2011)

Table 1 (continued)

	Performance-based models	Wolfgang Feist’s “Passivhaus standard” in the late 1970s (Feist, 2008)	Topographical, structural, acoustic, energy and other performance simulations	Michael Hensel, Filippo Tessari, Rafael Sacks, Mark Goulthorpe	BSERT Centre in London by Hensel, The Thesis Building in the Politecnico di Milano by Tessari
DIGITAL MORPHOGENESIS	**Topological architecture**	Deconstructivists such as Peter Eisenman (Eisenman, 1998)	Topology, a branch of mathematics, properties that are preserved through deformations	Peter Eisenman, Michael Hansmeyer	Holocaust Memorial Museum (Eisenman, 2005)
	Parametric architecture	Patrik Schumacher (Schumacher, 2008)	Parametric design, design elements are defined by variables that can be adjusted	Farshid Moussavi, Patrik Schumacher	Museum of Contemporary Art Cleveland (Moussavi, 2012); (Zaha Hadid Architects, 2008)
	Animate architecture	Greg Lynn (Lynn, 1996)	Animation techniques, such as keyframing or particle systems	Greg Lynn, Kas Oosterhuis	MetaCity/Data Cloud (Oosterhuis, 2006); blobitecture (Lynn, 1996)
	Metamorphic architecture	Neil Denari (Denari, 1989)	Transformation or metamorphosis	Neil Denari, Frédéric Migayrou, Michael Jakob, Manuel Kretzer	NMHT (Denari, 1991); Centre Pompidou (Migayrou, 1977)
	Isomorphic architecture	Michael Hansmeyer (Hansmeyer, 2012)	Isomorphic correspondencebetween two or more objects that have similar characteristics	Michael Hansmeyer, Benjamin Dillenburger, Markus Schaefer, Thomas Auer, Achim Menges	Digital Grotesque (Hansmeyer, 2012)

Table 1 (continued)

	Genetic algorithms	John Frazer (Frazer, 1995)	Algorithms that mimic the process of natural selection in order to generate new design options	John Frazer, David Krawczyk, Michael Weinstock, Karl Sims	An Evolutionary Architecture (Frazer, 1995); The Unseen (Krawczyk, 2011)
	Performative architecture	Wolfgang Feist's "Passivhaus standard" in the late 1970s (Feist, 2008)	Computational design tools and methods, such as computer simulations or optimization algorithms	Chris Wilkings, Frédéric Migayrou, Achim Menges, Michael Hensel	Hearst Tower (Foster, 2006), Guangzhou Opera House (Hadid, 2010)

- **Physical form-finding:** This refers to the conventional tools and methods used to explore and generate form, such as hand drawing and model making as physical prototyping (Chilton, 2012; Belanger, 2017; Kuo et al., 2021). It involves constructing a physical model of the structure and testing it under different loads to determine its optimal shape (Kramer, 2015; Dai, 2019). This can be done using methods such as hanging models and cable-and-buckle models (Dai, 2019). This approach has the advantage of being intuitive and easy to understand (Gao et al., 2019; Lau et al., 2021), and it can be effective for exploring simple forms and designs (Kim, 2014). However, they can be time-consuming and labor-intensive (Nash, 2021), and they may not be suitable for more complex or intricate forms (Cuff, 2011; Nash, 2018).
- **Digital design models:** This refers to using computer-aided design (CAD) tools and software to explore and generate form, often based on parametric or performance-based design principles (Kim, 2014). These approaches can be highly efficient and accurate, and they can enable the creation of designs that are optimized for specific performance criteria (Cuff, 2011; Nash, 2021). However, they can be expensive and require specialized software and hardware (Belanger, 2017; Kuo et al., 2021), and they may not be suitable for more conceptual or exploratory design processes (Chilton, 2012).
- **Digital morphogenesis:** This refers to the use of computational techniques and tools to explore and generate form, often based on principles from nature such

as growth, evolution, and self-organization (Cuff, 2011; Gao et al., 2019; Nash, 2021). These approaches can be highly effective for exploring and generating complex and intricate forms, and they can enable the creation of designs that are not possible using traditional techniques (Kim, 2014). However, they can be difficult to understand and use for those without a strong background in computer science or programming (Chilton, 2012).

Overall, each form-finding approach has its own strengths and limitations, depending on the specific design context and requirements (Kim, 2014). It is important for designers to be aware of the different form-finding approaches and to be able to choose the most suitable approach for a given design problem (Cuff, 2011) since the form-finding process is not characterized by a single definition. It varies depending on the various perspectives, problems, and goals. According to the desired goals, each approach can be combined in many different ways since they share common approaches and tools. For instance, a physical form-finding approach driven by nature has a biomimetic approach in its roots, which is also fundamental for understanding the natural algorithms in digital morphogenesis classification. That is why none of the architects actually follows a single model or approach as they combine multiple to achieve desired goals. For instance, Gaudi inspired from nature, for sure, however, he used catenary geometries to simulate hanging chains in order to achieve structural performance. In this manner, he adopted a form-finding approach that is both driven by nature and performance-based. The details regarding each form-finding approach are given in the following sections.

2.1.1. Physical form-finding

The use of physical models for form-finding, or the process of determining the optimal shape of a structure to support a given set of loads, dates back to at least the ancient Greeks. The Greek mathematician and engineer Archimedes is credited with using physical models to explore and demonstrate the principles of statics and hydrostatics, and his work is considered to be an early example of form-finding (Gürdal, 2008).

In the field of architecture and engineering, the use of physical models for form-finding has continued to evolve over time. In the 18th and 19th centuries, architects and engineers such as Giovanni Battista Piranesi and August Perret used physical models to explore and demonstrate the structural behavior of their designs (Bruhn, 2003). In the middle of the 20th century, the use of physical models for form-finding was further developed and refined through the work of architects and engineers (Otto, 1975).

In the 1960s and 1970s, the architect and engineer Buckminster Fuller developed the concept of tensegrity, which involves using tension and compression to create structural stability. He used physical models to explore and demonstrate the principles of tensegrity (Fuller, 1975). In the 1980s and 1990s, the architect and engineer David Billington developed the use of cable-and-buckle models as a tool for form-finding (Billington, 1985).

In the 2000s and 2010s, architects and engineers such as Jörg Schlaich and the Institute for Lightweight Structures and Conceptual Design at the University of Stuttgart have continued to develop and refine the use of physical models for form-finding, particularly in the design of cable-net structures (Schlaich et al., 2009). In the following years, the architect and engineer Michael Hansmeyer used physical models and digital simulation tools to explore and generate complex, ornamental forms in his work, such as the Digital Grotesque project (Hansmeyer, 2012). The architect Achim Menges and his team at the Institute for Computational Design at the University of Stuttgart developed the use of material-based design computing, which involves the use of physical models and digital simulation tools to explore and optimize the form and performance of structures made from responsive materials (Menges et al., 2014).

The architect and engineer Neri Oxman and her team at the Mediated Matter group at the Massachusetts Institute of Technology have used physical models and digital simulation tools to explore and optimize the form and performance of structures made from responsive materials, such as the Silk Pavilion project (Oxman et al., 2014). The architect and engineer Benjamin Dillenburger and his team at the Digital Building Technologies group at ETH Zurich have used physical models and digital simulation tools to explore and optimize the form and performance of structures made from responsive materials, such as the Hy-Fi project (Dillenburger et al., 2015). In the 2020s, the architect and engineer Ammar Eloueini and his team at the Digital Building Lab at Carnegie Mellon University have continued to develop and refine the use of physical models and digital simulation tools for form-finding, particularly in the design of timber structures (Eloueini et al., 2020).

After reviewing the development of physical form-finding and its incorporation to computational form-finding, it can be concluded that the emergence and advancements in computer technology in architectural design starting from the late 1960s brought in the prospect of employing computers to develop architectural forms based on quantitative data (Grobman and Ron, 2011). In other words, the quantitative characteristics of the architectural form and qualitative, cognitive, and perceptual characteristics have received major weight in the conventional approach of form generation. This notion has been central to philosophical and theoretical approaches and ideas all across the history of architecture, which simultaneously resulted in supporting image-based models of form such as typology and shape grammar studies (Grobman and Ron, 2011).

It is clear that many architects and engineers have used both physical and computational approaches to form-finding, either separately or in combination, to take advantage of the strengths of each approach. Physical form-finding has the advantage of being intuitive and easy to understand, and it can be effective for exploring simple forms and designs (Kim, 2014; Lau et al., 2021). It can also be used to demonstrate and communicate structural concepts to a broad audience (Bruhn, 2003). However, physical form-finding can be time-consuming and labor-intensive (Nash, 2021), and it may not be suitable for more complex or intricate forms (Cuff, 2011; Nash, 2018). Computational form-finding, on the other hand, can be highly efficient and accurate, and it can enable the creation of designs that are optimized for specific performance criteria (Cuff, 2011; Nash, 2021). It can also be used to explore and generate complex and intricate forms that are not possible using traditional techniques (Kim, 2014). However, computational form-finding can be expensive and require specialized software and hardware (Belanger, 2017; Kuo et al., 2021), and it may not be suitable for more conceptual or exploratory design processes (Chilton, 2012).

By using both physical and computational form-finding approaches, architects and engineers can take advantage of the strengths of each approach and create designs that are optimized for a variety of criteria.

Within the framework of this dissertation, physical form-finding is divided into four main categories based on the literature (Kolarevic, 2003; Elshanwany, El-sayad and Nasser, 2020): Form-finding driven by nature; driven by geometry; driven by context;

and driven by performance. Although there is a major shift from physical to digital, there are also common methodologies, tools, and goals through inherited properties from traditional to digital.

- **Driven by Nature:** Physical form-finding driven by nature refers to the use of physical models and prototypes to explore and generate structural forms based on natural phenomena and principles. This can involve using physical models of natural structures or systems, such as shells, bones, or plants, as inspiration for the design of man-made structures (Chilton, 2012; Gao et al., 2019). It can also involve using physical models to explore and understand the behavior of natural systems under different conditions, such as wind, water, or gravity (Bruhn, 2003; Nash, 2021). Physical form-finding driven by nature has the advantage of being intuitive and easy to understand, and it can be effective for exploring simple forms and designs (Kim, 2014; Lau et al., 2021). It can also be used to demonstrate and communicate structural concepts to a broad audience (Bruhn, 2003). One common method of physical form-finding driven by nature is the use of hanging models, in which a physical model of the structure is suspended by wires or cords and subjected to different loads or forces (Dai, 2019). This can help to understand how the structure will behave under different conditions and to identify the optimal shape and configuration for a given set of loads (Kim, 2014; Lau et al., 2021). However, physical form-finding can be time-consuming and labor-intensive (Nash, 2021), and it may not be suitable for more complex or intricate forms (Cuff, 2011; Nash, 2018). A form-finding process driven by nature also employs biomimetic approaches in which the form, system, or organization of living organisms are adapted in a systematic manner, beyond replication. By advocating for universal design principles, abandoning self-expression and the simple replication of past styles, the architects and designers have turned their attention to science and nature including Hector Guimard and Santiago Calatrava, as recent examples, designers of the entrance of the Paris metro station and the City of Arts and Sciences in Valencia, both of which were based on mimicking the sophisticated processes of living organisms (Lotfi, 2014) rather than just copying their form and aesthetic appeal.

- **Driven by Geometry:** The form-finding process driven by geometry refers to the use of geometric rules and proportions as the main drivers of the process of form-finding. Many notable architects, such as Louis Sullivan, who created decorative patterns using quadrature and triangulation, and Frank Lloyd Wright, whose design for the Unity Temple in Chicago (1908) was based on a modular grid with dimensions of 2 meters that was refined and emphasized with dimensions derived from spherical geometry (Elshanwany, El-sayad and Nasser, 2020). In his book Modulor (1948), Le Corbusier later attempted to build a design method based on proportions and identified the golden ratio as the secret to beauty. He also used his well-known proportional scheme in two of his most significant creations, the Notre Dame du Haut Chapel in Ronchamp (1954) and the Phillips' Pavilion in Brussels (1958), demonstrating the usefulness of modular proportions and geometric calculations as a tool for creating novel designs (Agkathidis, 2015).

- **Driven by Context:** Some of the architects contributed to the postmodern design movement by relying on the properties of the site, the impact of the surrounding environment, and the incorporation of morphological and typological aspects. One of the most well-known architects of this style, Aldo Rossi, utilized the fundamental elements and forms found in many ancient Italian towns, such as the octagon, column-rows, arches, etc., independent from program or proportion. The Teatro del Mondo project in Venice in 1979 utilized the octagonal tower design, which can illustrate the form-finding process driven by the context (Jormakka, 2013).

- **Driven by Performance:** In contrast to the earlier form-finding drivers, some of the architects and designers employed a whole new method that was based on assessing the structural performance, the characteristics of the construction materials centering on the minimal surfaces and forms, while developing relationships with the environment played a supplementary role (Kolarevic, 2003). Shukhov Vladimir is one of the most notable pioneers of performance-driven form-finding (Elshanwany, El-sayad and Nasser, 2020). The hyperboloid water tower designed for the Nizhny Novgorod industrial

> exhibition in 1896 is one of his most significant works. This is the first building made of metal from a hyperboloid diagrid structure which can also be seen in his later designs, including the communication tower at Moscow, Russia. It is the synthesis of a mathematical model, structurally enhanced design, and material efficiency (Kolarevic, 2003; Cordoso, 2017).

Although there is a distinction between each approach to form-finding, the main goal is to optimize the form according to certain parameters. These parameters can be related to internal factors such as the form, function, structure, or topology; whereas the external parameters can become significant drivers in the performative form-finding process such as environmental factors. By the nature of Architecture, these approaches do not have to be necessarily employed individually, there are also examples showing multiple combinations through multi-objective optimization and form-finding in a conventional manner. Numerous designers, architects, and engineers throughout different centuries employed physical methods that were very similar to today’s computed twins and are still highly prevalent today (Otto and Nerdinger, 2005). Therefore, it would be wrong to consider that form-finding has its roots in the digital era, however, it has become a powerful tool for digital design over time.

2.1.2. Digital Design Models

Naturalists began a movement in the 18th century to better comprehend the universal laws of form in order to reveal the logic of the formation of living organisms (Goldsmith, 2014). A modern understanding that there are universal laws derived from fundamental math and physics and that reflect the growth and form in biological systems was developed during the early 20th century by pioneers such as D'Arcy Wentworth Thompson, despite the fact that this idea didn't attract much attention at the time. Thompson studied the relationship between mathematical models and forms in nature and showed how, for example, jellyfish forms and liquid droplets had a lot in common. His work On Growth and Form (1917) helped to pave the road for the study of nature and was crucial to the eventual development of the area of biomimetics (Goldsmith, 2014).

The acknowledgment of living organisms has grown in popularity as a result of Thompson's link between natural systems, forms, and structures, and their underlying defined principles. The natural patterns adopt basic mathematical models. Soap film studies have provided an understanding of minimal membrane structures; bee hives have provided a formulation of honeycomb structures, which are now used in lightweight panel systems; and an understanding of photosynthesis has given a rise to the developments of photovoltaics as a renewable energy supply; and swarms have taught us how to build dynamic structures (Goldsmith, 2014). Urban planners have even focused on non-planned urbanization, where social, cultural, and environmental constraints allow communities to grow gradually as a result of individual actions and collective reactions. This was first described by Bernard Rudofsky in From Architecture without Architects in 1964.

There is a long-standing misconception that the process of designing an architectural structure is rational and linear and that the architect is in some way imitating God the creator (Goldsmith, 2014). While natural systems are built on processes and coordination developed over the interactions between the elements of initially disorganized systems, physical form-finding promotes a design approach better suited to discovering shapes based on the individual vision of the designer. In this manner, form-finding in natural systems differs from what is called shape-finding.

In the form-finding processes that fall into digital design models classification, the designer investigates natural dynamics to establish organizational patterns for the project. It is a study of the capacity for optimal form discovery and dynamic adaptation. The form's beauty emerges naturally from the evolved natural forms rather than having to be intentionally created. Methodologies for form-finding of complex geometries that are driven by newly explored structural systems, digital fabrication methods, and interactions between tension structures and components led to the emergence of the phrase “form follows force” with a constant emphasis on a non-linear/cyclical problem-solving (Sasaki, 2014).

We witness historical instances of this form-finding method in architecture in the works of Felix Candela in Mexico, Pier Luigi Nervi in Italy, Frei Otto in Germany, and Buckminster Fuller in the US. The examples include Candela’s concrete hyperbolic parabolas in the High Life Textile factory in Coyoacun, Mexico City in 1955 (Garlock and Billington, 2014); Pier Luigi Nervi’s curved ribbed thin-shell concrete dome in Palazetto dello Sport in Rome for the 1960 Olympics (Iori and

Poretti, 2013); Frei Otto’s a steel cable net with acrylic panels in Olympic Stadium in Munich in 1972 (Otto and Glaeser, 1972); and Buckminster Fuller, renowned for his geodesic dome based on struts and cables as a tensegrity structure (Fuller, 1975).

The following two examples provide a clear illustration of the differences between the two approaches: Shape-finding and form-finding. The first shows a soap film model that Frei Otto used to understand the conoid form of a tensile structure that he used in his design. The second is a sketch from John Utzon's early concept for the Sydney Opera House, where he created the curved forms by clamping a steel ruler in a bench vise (Goldsmith, 2014). The soap film model depicts a minimal surface with uniformly distributed tension. This minimum surface principle converges into a tensile structure with uniform loads and without fabric deformation. On the other hand, the organic form of Utzon appears to be efficient but requires extensive technical manipulations to translate these unconventional forms into a constructed form. Ove Arup and his company, which engineered these concrete shells, were able to develop the use of epoxy resins to bond thin joints of precast concrete units, and they approached the project as a problem-solving exercise in the conventional architect-engineer relationship (Jones, 2006).

Today, we see the concept of shape-finding utilizing formal ideas and occasionally analysis algorithms that are categorized according to different criteria. The work of Zaha Hadid and Santiago Calatrava can be given as the current examples of the shape-finding methodology (Goldsmith, 2014). Edifici Torre Espiral in Barcelona by Hadid where the idea of the project is defined as "shooting in from outside the frame, the thread winds itself loosely into a semblance of a structure" is an example of a translation of a sketch into a collection of building slabs that form a weaving around a central element (Zaha Hadid Architects, 2012). The initial idea starts as a design approach led by the intuition of the architect, however, the knowledge of physics and structural optimization is still embodied, despite the fact that these aspects are incorporated later in the design process (Goldsmith, 2014).

Several of Calatrava's projects are inspired by his interest in birds, which is also evident throughout his several works (Goldsmith, 2014). For instance, Calatrava converted the aesthetic shapes of an open wing into their physical manifestations in the World Trade Center Transportation Hub. The form of the skeleton was reinterpreted as a structural component through the abstraction of *"...a bird released from a child's hands"* (ArchDaily, 2016).

In comparison with this idea, Adrian Smith Gordon Gill Architects, which is accountable for several of the highest structures in the world (Smithgill, 2016), is known for their bigger-scale applications through form finding. China's Wuhan Greenland Center, a 119-story tower with a floor area of over 300,000 square meters, built in 2016, minimizes surface flow on the glazed facades by using aerodynamic wind simulation, and the wind resistance and vortex force that accumulates on extremely high towers were reduced by the cylindrical mass, softened corners, and spherical top, allowing the use of less structural material (Fu et al., 2012). The openings in the curtain wall help to relieve wind pressure on the tower. It is possible that the scale of the project demands a form-finding approach instead of a shape-finding method since extremely tall buildings become increasingly reliant on building physics, necessitating larger teams to integrate all the fragmented information into a synthesis building design.

In the literature, digital design models are sub-categorized into three: Formation, generation, and performance based on form-finding approaches and tools (Kolarevic and Malkawi, 2005; El-Sayed, 2010; Cayetano, 2019). This classification offers a framework that defines a taxonomy for digital design models and the accompanying technologies, which enables the reading and understanding of the connections between design concepts and terminology. The framework includes formation-based, generative-based, and performance-based models.

- **Formation-based models:** Given how much information is integrated into the building model throughout the form-finding process, it is thought of as a type of event, rather than a sequence of static frames. In comparison to straightforward ideological declarations, narratives, analogies, or reproduction, this repetitive and integrative application has more potential to resonate on multiple layers and produces unexpected and disruptive impacts (Elshanwany, El-sayad and Nasser, 2020). Since the digital design theory changed the notion of the form into the concept of formation, the conventional methods of communicating the paper-based design concept have lost their relevance as an intellectual framework for explaining the procedures and knowledge involved with digital design. Forming is a major shift from graphical representations and images because digital design models are being used to create design concepts as well as to explore complex geometries (Terzidis, 2003; El-sayed, 2010). Animation and parametric design, both of which heavily rely on topology, are the digital technologies that are connected to the formation design concept. While parametric modeling established the idea of topological differences, formation by animation offers the concept of dynamic design (Al-sayed, 2010). When using parametric modeling, the form is represented by a set of parameters rather than by its shape, and by changing the values of these variables, an endless number of possible formations can be generated (Grobman and Neuman, 2012). it's a concept that evolved from parametric design (El-sayed, 2010; Grobman and Neuman, 2012) which has been around for decades. So many individuals and groups have contributed to the development of this concept, however, some notable pioneers in the field of parametric design and formation-based models include Michael Hansmeyer and Benjamin Dillenburger (Hansmeyer and Dillenburger, 2012), who in the early 2000s developed a system for building complex architectural shapes using a process called "digitally fabricated architecture" and from that, it became a fundamental concept in the field of digital design. Another pioneer in this field is Michael Weinstock (Weinstock, 2011), an architect and professor who in the early 2000s developed a method called "responsive architecture" where the architecture responds to real-time data and changes in the environment to create dynamic and ever-changing designs.

- **Generation-based models:** In contrast to formal models, the generation type of model of digital design is defined by the inclusion of mathematical mechanisms for generative processes, which produces formations. Evolutionary models and shape grammars are two of the most significant patterns utilized in generation-based design (Kolarevic and Malkawi, 2005, p. 30; Cayetano, 2019). The first method, Evolutionary models, is based on modeling the processes of nature, including growth, reproduction or other metabolic activities (El-Sayed, 2010). The latter, shape grammars, offering a computational method for formulating generative systems, is the process in which form is determined by a range of variables and parameters connected to each other within a particular environment and geometries (Gu and Behbahani, 2018). This method has various uses in topological investigations.

- **Performance-based models:** According to the classification of digital models, the basis of performance models is the simulation. Numerous digital methods are employed in simulation for the assessment of the performances of a structure. Modern digital design methods describe a transition away from statistical simulation to the simulations of building performance to develop and anticipate emerging architectural forms (Kolarevic and Malkawi, 2005; Hensel, 2010; Caetano, 2019). The improvements in the performance are realized through iterations during the design's preliminary phases of this method, as opposed to looking at building performance and adapting it to the outcomes. As stated by this strategy, effectiveness is the capacity to engage with a specific object's numerical properties as well as other qualities such as topographical, structural, acoustic, and other performance simulations (Oxman, 2008).

Formation-based models of form-finding, characterized by the integration of a large amount of information into the building model, have the potential to produce unexpected and disruptive impacts (Elshanwany, El-sayad, and Nasser, 2020). These models often utilize animation and parametric design, which rely on topology and the concept of dynamic design, respectively (Terzidis, 2003; El-sayed, 2010). In contrast, generation-based models involve the use of mathematical mechanisms for generative processes, such as evolutionary models and shape grammars, to produce formations (Kolarevic and Malkawi, 2005; Cayetano, 2019). Performance-based models, on the other hand, focus on simulation to assess the performance of a structure, with an emphasis on improving performance through iterations during the design process rather than adapting to the outcomes of building performance (Hensel, 2010; Oxman, 2008). When two or more of these types of models are combined, the resulting digital design model may incorporate multiple layers of information and processes, potentially leading to more complex and nuanced design concepts and outcomes (Grobman and Neuman, 2012; Gu and Behbahani, 2018).

2.1.3. Digital Morphogenesis

The digital revolution has had an impact on architectural design since it has led to a rise in the use of information technology that lets designers experiment with novel forms and challenging geometries. They are no longer utilized for drafting and representation purposes, but they are still capable of producing an endless number of architectural solutions and transformations to satisfy particular design criteria. Since computational generative methods open up new dimensions for ideas and creativity, these new forms cannot be expressed by conventional and outdated methods and must instead be computed (Kolarevic, 2003). Today, the digital morphogenetic form-finding approach is one of the widely used methodologies in the design process in which forms are generated based on a set of rules or algorithms on various platforms such as Processing, Rhinoceros, Grasshopper, and other available scripting platforms (El-Sayed, 2010).

The word *morphogenesis*, *which* originated from the Greek language, has two parts: “morph” meaning formation (or form), and “genesis” meaning birth. Therefore it literally means the birth of the form (Terzidis, 2003). In this approach, the static types of conventional design procedures in digitally created forms have been replaced with continuous and dynamic transformations, which are generally characterized by unpredictable outcomes.

In digital morphogenesis, the vertical section of the structures plays a crucial analytical role, while Modernism's horizontal plan is no longer the design's primary generator. The digital methods have undergone a major transition from form-shaping to form-finding, where the constant is replaced by the variable and distinctiveness by variety (Turrin, von Buelow and Stouffs, 2011). Digital morphogenesis thus emphasizes the dynamic characteristics and aesthetics, which are not created in accordance with predetermined horizontal layouts but rather are created using a variety of digital and physical tools (Kolarevic, 2013).

Digital morphogenesis is a self-organizing process that follows the development of organisms, from which architects might learn (Hensel, Menges and Weinstock, 2006). The application of quantitative generative methods to identify materials through form and the growth of their genesis was another definition for digital morphogenesis (Oxman and Oxman, 2013). In parallel with this definition, the form-finding methods can be conducted based on the primary regulating factor including mathematical, structural, building materials, ecological, manufacturing, or performance.

Within the framework of this dissertation, the digital morphogenesis approach to form-finding is divided into seven subcategories based on the literature (Kolarevic, 2003; Elshanwany, El-sayad and Nasser, 2020): Topological architecture, parametric architecture, animate architecture, metamorphic architecture, isomorphic architecture, genetic algorithms and performative architecture, each of which corresponds to digital morphogenesis and has particular characteristics in terms of form-finding. Although there are differences in objectives and goals, most of them share similar principles and tools.

- **Topological architecture:** Topological architecture is defined as a design strategy that has departed from the contradictions of the deconstructivist method by developing a more adaptable and communicative strategy (Elshanwany, El-sayad and Nasser, 2020). In this approach, the flow and connectivity emerge as a result of a design approach that differs from the Euclidean geometry of discrete volumes represented in Cartesian space, since the relational curves and surfaces, known as Non-uniform rational B-Splines (NURBS), creates the geometric form. By employing this method, designers can modify the geometry by moving the control points, the weights that correspond to them, and other knots that constitute the geometry. Additionally, they enable computationally feasible topographical space configurations (Kolarevic, 2003; Agkathidis, 2015). A notable example is the Mobius House, which was completed in 1998 and was designed by the Dutch architect Van Berkel in Amsterdam. The Mobius strip, one of the topological forms, served as inspiration and methodology for the project. Although the final form differs from its preliminary form, the same topological properties apply for both through folded sheets made from a Mobius strip.

- **Parametric architecture:** In the literature, there are two approaches to parametric design/architecture. The first approach assumes that all designs are parametric since they are dependent on internal and external factors, including orientation, structural loads, solar irradiation, wind forces, or restrictions of vision (Suyoto, Indraprastha and Purbo, 2015). The other methodology defines parametric architecture as employing specialized software, such as Grasshopper, Maya MEL, and Rhino Scripting platforms, to be able to enhance the configuration of design elements through customizable interconnections (Woodbury et al., 2010). To illustrate, a series of environmental optimizations for high-rise morphologies in dense urban contexts was created by Jyoti (2016) by altering certain values and parameters and producing an endless number of design possibilities.

- **Animate architecture:** Greg Lynn is credited as being the first architect to employ animation software for architectural form finding, not necessarily for rendering. The coexistence of motion and force at the time of formal conception serves as its defining characteristic. Force alters the atmosphere as a starting point, which impacts both motion and specific form inflections (Lynn, 1999). St. Gallen Kunstmuseum in Switzerland designed in 2001 can be given as an example.

- **Metamorphic architecture:** The foundation of this strategy is the creation of a simplified form, which is manipulated by desired transformations, such as bending, twisting or morphing, etc. which are specified in accordance with the design concept. An animation software is used to enable the expression of the building and its surroundings before allowing the user to select the best frames for the animation by introducing a fourth dimension, the time dimension, to the transformation procedures (Hensel, Menges and Weinstock, 2006). Kinetower, designed by Kinetura, gives emphasis on the metamorphosis of space, optimized in relation to functional and environmental requirements, what is called as controlled spontaneity of buildings.

- **Isomorphic architecture:** Isomorphic architecture employs geometric forms, known as meta clay, meta-balls, or blob models, which are solid models with volume and forces of attraction. The surface size, mass with respect to other elements, and the geometry’s field of impact are defined as a relational region in which the elements merge or transform under the effect of one another. When two or more points are close to one another, the following possibility exists. They either modify their shared surfaces under the influence of the gravitational forces or they interact with one another at their centers or zones of deflection and union to form a singular homogeneous surface (Waters, 2003). The BMW Pavilion in Frankfurt, Germany, constructed in 2001 by Bernard Franken from ABB Architekten, for instance, is an example of isomorphic architecture in which the drop of water represents the abstract form of clean energy, powered by hydraulic power, hydrogen, and solar energy.

- **Genetic algorithms:** Based on natural selection and evolution, genetic algorithms are a type of artificial intelligence (Hensel, Menges and Weinstock, 2006) that mostly rely on genetic principles closely related to those found in biological organisms. It is frequently utilized while improving existing design proposals or beginning with new ones. It demonstrates a significant capacity to produce a great number of choices in a short period of time, facilitating designers in their decision-making process (Lotfi, 2014). The genetic algorithm (GA) developed by John Holland and published in 1975's "Adaptation in Natural and Artificial Systems" attempts to simulate evolution's logic in a Darwinian interpretation with the help of a result of the discovery of the structure of DNA (Watson and Crick, 1953). The primary aspect that should be considered as novel in comparison to his forerunners is the introduction of the crossover operator, introduced through reproductive systems. Holland's approach is the one that most closely resembles the biology science of genetics due to his vocabulary (Varela, 2013). Karl Chu (2006) emphasizes metaphysics in architecture and mathematical processes by using the computing power of computers to construct a genetic architecture. He started by developing an algebraic equation in which three basic preparatory variables were used to create six primary groups, and he assigned three letters to each component. Chu (2006) researched ongoing advancements in subsequent generations, such as the X-Phylum project.

- **Performative architecture:** When designing cities, buildings, landscapes, and infrastructure networks, the performative architecture incorporates numerous criteria based on performance assessment as the primary goal for the design process (Hensel, 2010; Cardoso, 2017). This method uses digital quantitative and qualitative methodologies in relation to modeling the building performance, allowing a multi-objective approach to the design of the built environment. It prioritizes satisfying the objectives of the design over the interest regarding its formative composition. Design that simulates various performances, including those that are spatial, social, cultural, economical or structural, thermal, and environmental (Kolarevic, 2003; Grobman and Neuman, 2012) is known as performative design. As an illustration to performative architecture, London City Hall, a remarkable structure created by Norman Foster in 2002, offers comprehensive energy solutions, and is designed to be eco friendly, as well as offering a river panorama (Schroeder, 2014), although it is also criticized for its energy efficiency rating in terms of an annual CO_2 emission. In this regard, several stages have been followed by the Foster architects. The initial design used a sphere with the smallest surface area at a particular volume, given that the form should have absorbed the least amount of heat. Therefore, minimal surface area was the best option from an environmental standpoint. By aligning the building's axis with the noon sunlight, the building's form had the least amount of exposed surface area. The side facades are curved, taking up the least amount of space towards the east and west when the sun is at its lowest angle. The majority of the building is rounded, which gives it the biggest field of vision facing the river when viewed from the north side (Elshanwany, El-sayad and Nasser, 2020). In order to comply with environmental restrictions, the architects adapted the form of the building in relation to solar energy, and a color-coded graphic was produced to illustrate how much energy was absorbed by each of the building's exterior frames throughout the course of the year (Fasoulaki, 2008).

2.1.4. Discussion

When the approaches introduced in this chapter are compared, it is clear that they share many characteristics, such as systematic, continuous, and dynamic variations and the ability to generate complex geometries using digital media and physical prototyping. They open up new possibilities for generating an endless amount of form proposals. In other words, they shift the emphasis from the concept of form-making or shape-finding to the concept of form-finding.

Aside from performance-oriented design, which prioritizes the performative aspects, other perspectives concentrate primarily on the qualitative and aesthetic aspects of the architectural form, resulting in solutions that may not be reasonable for everyone from an aesthetic standpoint. In this case, building performances such as functional, environmental, structural, or acoustic, become secondary. Therefore, the designer chooses a less-than-ideal option that might satisfy the aesthetics criteria.

It is crucial to take into consideration a variety of factors, including the interplay amongst design objectives and building form, aesthetic concerns and construction technologies, the influence of the immediate and larger context on the design, user preferences and embodied and operational costs. It is important to note that a comprehensive form-finding approach creates a more balanced configuration of various qualitative and quantitative dimensions of design, moving away from a design focused solely on aesthetic and other visual concerns, towards a design justified by its performance. This dissertation particularly focuses on computational structural analysis within the context of generative performative form-finding.

2.2. Computational form-finding for structural performance

Although the terms structural optimization and form-finding are often used interchangeably, they refer to different methods and tools in architectural design and engineering. Structural optimization is a method that uses mathematical models to optimize the design of a structure based on certain criteria, such as weight, stress, or cost. The goal of structural optimization is to find the optimal configuration of a structure that meets certain performance criteria, such as strength or stability (Bendsoe, et al., 2004). Form-finding, on the other hand, is a method that focuses on finding the shape of a structure that is in equilibrium with the forces acting on it (Péclard, et al., 2018). It uses computational methods to discover the natural shape that can exist for the given material, loading and constraints. The goal of form-finding is to find the overall shape of the structure and how it deforms under load, rather than just optimizing individual components of the structure.

One key difference between the two methods is the level of detail at which the design is optimized, as structural optimization is typically done at the component or member level, whereas form-finding is done at the overall shape level. Both structural optimization and form-finding are important methods in architectural design and engineering, and they can be used in conjunction with one another to find the optimal solution for a given structure.

The design and construction sectors benefit greatly from the application of these quantitative methodologies to material-efficient or cost-effective systems (Vanderplaats, 2006). The building industry forms a significant part of global natural resource consumption, and these methods and tools can help to reduce this, thus enhancing the sector's sustainability. Furthermore, by automating the sizing operations for structural elements, they have the potential to minimize not only building and engineering costs but also the time spent on construction planning and implementation (Waimer, La Magna, and Knippers, 2013). They also contribute to future innovations for certain building components or materials in terms of size, form, and topological distribution (Bao et al., 2019).

2.2.1. Classification of tools and methods

Typically, structural optimization and form-finding strategies seek to determine the optimal dimensions of structural components; optimize the shape of the structure; and seek to identify the optimum spatial distribution of construction systems or structural components (Mei and Wang, 2021). Design approaches for constructability are rapidly evolving, however, each specific manufacturing or assembly method has its own technological constraints, and expressing them in a controllable mathematical form is typically far from straightforward (Favi et al., 2021).

There are a number of uncertainties in real-world structural application challenges. Forces, loads, material properties, dimensions, and other parameters may differ from those estimated during the design process. Such inconsistencies might have a negative impact on structural performance. As a result, it is critical in structural optimization not only to optimize the performance of the schematic design but also to make sure that its vulnerability to inconsistencies is kept to a minimum. In order to do that, inconsistencies could be incorporated into the optimization process using resilient and reliability-based design optimization methodologies.

In recent years, there has been a growing interest in the use of form-finding approaches to explore and optimize the performance of structures. These tools and methods, which range from physical and conventional approaches to digital design models and digital morphogenesis, have been utilized by researchers and practitioners in the fields of architecture, engineering, and computational design.

One of the earliest form-finding approaches is the catenary form-finding technique which is based on the principles of tension and compression as defined by Hooke's Law. This technique was popularized by architects such as Antoni Gaudi in the early 20th century, who utilized it in the design of iconic structures such as the Sagrada Familia and Casa Battlo (Souto, 2010).

Another popular form-finding approach is the use of digital design models and genetic algorithms, which are inspired by the principles of natural systems. This approach, known as digital morphogenesis, has been advocated by the researchers such as Michael Weinstock (Weinstock, 2011) and Andrew Payne (Payne, 2009).

In addition to these form-finding approaches, there are also various tools and methods that have been developed to analyze and optimize the structural performance of structures. These tools have been utilized by practitioners and researchers to explore the potential of a wide range of materials and design strategies, with a focus on achieving optimal structural performance and energy efficiency. Overall, the field of form-finding is constantly evolving, with new tools and methods being developed to better understand and optimize the structural performance of structures. It is expected that this trend will continue in the future, with new advances in computational design and simulation technology driving the development of even more sophisticated form-finding tools and methods (Adriaenssens, 2014).

There is a classification in the literature (Figure 2) regarding structural optimization and form-finding, depending on the goal and the characteristics of the problem, e.g. static or dynamic, introduced by Block and Veenendaal (2012).

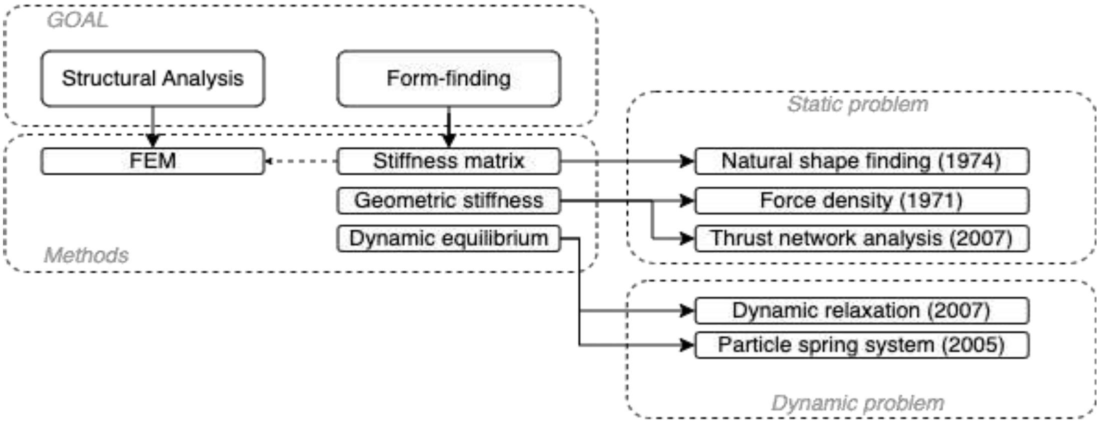

Figure 2. Classification of structural optimization and form-finding (Source: Block and Veenendaal, 2012)

Although there are many similarities and common methods incorporated in both, there are also specific differences. Form-finding, from a structural point of view, is the process of determining a self-standing form of equilibrium for a system related to a given set of loads, and boundary conditions, starting from a random initial geometry (Veenendaal and Block, 2012). Currently, as computational capabilities have been enhanced, numerical simulations can be performed, among which Finite Element (FE) based methods, Dynamic Relaxation (DR), and Force Density Method (FDM) are widely acknowledged and used (Adriaenssens et al. 2014).

Structural optimization is a knowledge-based process, whereas form-finding aims to develop diversity rather than knowledge (Block and Veenendaal, 2012). In structural optimization, the simulation is based on the material and on solid geometry, which is challenging to integrate with any future procedure. A given solution can be evaluated using computationally intensive approaches such as the Finite Element Method (FEM). These methods comprises analysis and optimization that necessitate a detailed definition of boundary conditions such as geometry, topology, and material, and loads.

On the other hand, the methods in the second category, form-finding, make it considerably simpler to carry out dynamic deformations based on non-linear behavior and control intricate interactions by using equations and parameters. These procedures are particularly ideal for developing visually and structurally accurate simulations. For instance, the Dynamic Relaxation method (DR), following the dynamic equilibrium principle, relies on resolving the balance of forces to emerge at a structure's static state.

Additionally, this approach yields the most varied outcomes while requiring the least amount of computer power (Veenendaal and Block, 2012).

The particle spring system (PSS), which was developed as one of the most recent form-finding tools in 2005 (Block and Veenendaal, 2012), is based on this latter technology. Each discrete object in a PSS must be comprehensible as a collection of points and each point is defined by its position, mass, and velocity. Understanding the repellent, attracting, or neutral relationship between two particles in the system helps to compute the evolution of the particle system using springs. As a result, interactive models with variables that transform the geometry in real time are technically feasible. Multiple design methods and tools (Figure 3) have been introduced in recent years relying on the PSS mechanism.

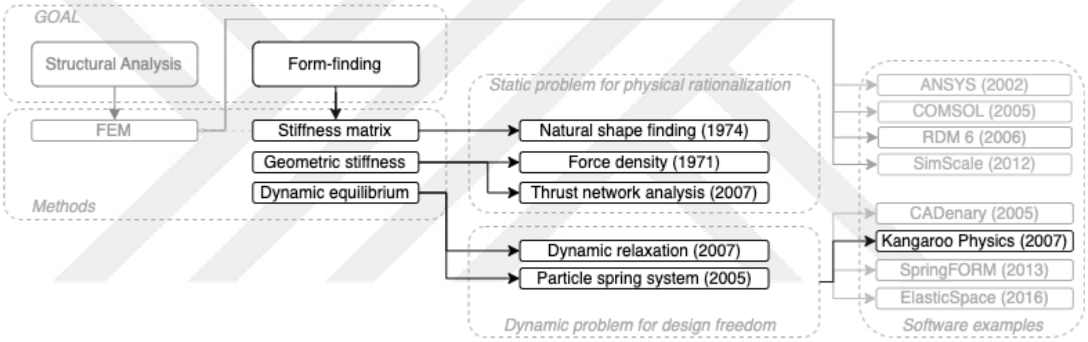

Figure 3. Available methods and tools for form-finding (Source: Block and Veenendaal, 2012).

Based on Gaudi's catenary system and providing a customizable tool for the emergence of compression-only vaults, the CADenary was developed in 2005 by Axel Kilian (Kilian and Ochsendorf, 2005). The SPRINGform was developed in 2013 for intricate geometries using hybridized dynamic bending and tension (Ahlquist et al., 2013). ElasticSpace is a real-time recursive topology algorithm that was createdin 2016 (Suzuki et al., 2017). The K2Engineering was developed based on the Kangaroo Physics library that provides changes that are similar to those suggested in this dissertation and is more focused on physical rationalization. Even though this plugin was referenced in a few publications (Melville et al., 2017; Bonavia et al., 2019), there are no articles that explain how it operates, even though the source code is accessible. However, the K2Engineering's existence demonstrates that there is a defect because it was necessary to create this plugin, yet this flaw has never been explicitly shown, despite being crucial for narrowing the gap between the user and the physical model and its variables. The objective of this dissertation is to narrow down this gap, first by demonstrating that a gap exists and then by suggesting a viable method and a customized tool for real-life applications.

2.2.1.1. Kangaroo Physics

The user interface for each of the above-mentioned tools has been streamlined, however, Kangaroo Physics is open-sourced, and implements a similar form-finding mechanism. Moreover, the form-finding method in Kangaroo Physics still has a few problems apart from its numerous strengths. Without demonstrating the complexity and potential of the material, it only depends on previously established techniques. That is why indicating a generic material type within the structural form-finding processes results in exact values and form unless different materials are not assigned or specific constraints are not given.

The Kangaroo Physics, developed in 2007 by Daniel Piker, is a plugin for Grasshopper, a visual programming platform for the Rhinoceros 3D, that enables the simulation of physical systems for form-finding in architectural design. With its origins in the physics-based simulation of flexible structures, Kangaroo Physics has been continuously developed and expanded to incorporate various other forms of simulations, including structural mechanics, material behavior, and mechanisms (Piker, 2007).

Despite its many advantages, Kangaroo Physics also has some deficiencies. One of the main challenges is its limited ability to simulate non-linear material behavior, such as large deformations and failure (Bechthold, 2010). Additionally, the accuracy of simulations can also be affected by the accuracy and quality of the input data, such as the material properties and loads, and the choice of solver settings (Piker et al., 2009).

In conclusion, Kangaroo Physics has established itself as a powerful tool for form-finding in various fields, and its algorithmic approach provides a versatile and efficient method for exploring design options. However, its limitations in simulating non-linear behavior and the need for accurate input data must be considered when using the tool.

2.2.1.2. Dynamic Relaxation in Kangaroo Physics operation

The form-finding process for tensile structures reflects the notion of form follows force where the geometry is determined by the interplay between topology and forces (Heitel and Fu, 2021). The Grasshopper can conduct mathematical operations, evaluate parameters, and process enormous amounts of data (Boon, Griffin and Papaefthimious, 2015). The Grasshopper's workflow enables users to develop a visual representation of code blocks connected by wires. These blocks primarily consist of parameters for storing data and components for performing operations that result in interpreted new data (Wurzer and Pak, 2012). The advantage is to analyze a given geometry and extract data from it, which can then be utilized to create new geometry with desired constraints and the introduction of loads. Kangaroo Physics implements a dynamic procedure to do a non-linear structural analysis of digital objects to seek a static equilibrium state in which tensile structures are perfect cases due to their behavior under tension forces (Heitel and Fu, 2021).

The Kangaroo Physics is an open-source form-finding and optimization tool that utilizes physics-based simulations to generate complex geometries, and it is built on top of the Grasshopper platform and is compatible with the Rhinoceros 3D (Piker, 2013). Using this open source data, a Kangaroo Physics operation, Particle-Spring System (PSS), was conducted within the computational form-finding process of this dissertation through creating an initial catenary geometry in the Grasshopper/Kangaroo Physics for interactive simulation, form-finding, optimization, and constraint solving (Figure 4).

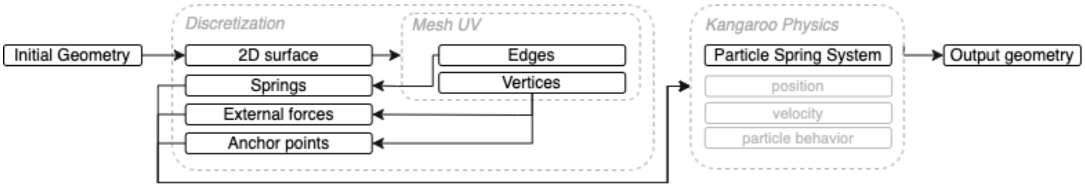

Figure 4. A generic description of the Kangaroo Physics workflow for form-finding

In order to work with the geometry in Kangaroo Physics, the mesh discretization process is essential in order to first divide it into vertices, edges, and surfaces. As desired, some of these vertices define where the anchor points are located, while some define where external or internal loads are applied. The edges become springs to be assigned within the solver using the PSS. The resulting geometry is a collection of curves that can be joined together to form a mesh (Piker, 2017).

In terms of the operation, the tool operates by creating a mesh of particles and connections, known as springs, that represents the structure to be optimized. The solver component is then used to iterate through the simulation, adjusting the positions of the particles based on the defined inputs such as goal objects, threshold, and tolerance (Piker, 2017). These inputs provide Kangaroo Physics with the necessary information to generate an optimized form that satisfies the defined constraints and goals.

One of the main advantages of Kangaroo Physics is its ability to simulate the behavior of elastic materials and structures, making it useful for form-finding tasks that involve materials such as fabrics, membranes, and bio-inspired materials (Piker, 2011). Another advantage is its ability to handle large-scale and complex geometries by utilizing parallel computing (Piker, 2017). Kangaroo Physics also offers various outputs such as iteration, vertices, and goal function outputs that can be used to evaluate the performance of the generated form. Additionally, the tool has been used in various fields including architecture, product design, and engineering (Piker, 2014).

The Kangaroo Physics algorithm functions by minimizing overall energy through the iterative movement of points (Piker, 2013). The various goals established within the algorithm define distinct energies that become null under certain geometric conditions. For instance, the length goal operates as a spring, in accordance with Hooke's law, resulting in zero energy when it is at its resting length. However, energy increases if it is stretched or compressed, with the energy increasing proportionally to the square of the deformation distance. Other goals are established based on geometric relations between the set of points they affect. Some of these goals, such as length, angle, and pressure, are rooted in physical elastic behavior, and can be related to standard material properties and units. Additionally, there are goals that are purely geometric in nature, becoming zero when certain conditions, such as circle tangency or quad planarity, are met. These goals can be used for finding geometry that satisfies certain fabrication constraints. Some goals are physically based, but not yet calibrated, such as the hinge goal for shell bending. These goals can model physical behavior qualitatively, but not in a way where numerical material properties can be directly applied (Piker, 2019).

When goals do not conflict, the algorithm can function as a geometric constraint solver by nullifying all energies (Dasari et al., 2022). However, when finding the deflection of a hanging cable, both the length and load goals will not be satisfied at the same time. In these cases, the algorithm finds the configuration with the least total potential energy, which can be a numerically accurate model of elastic deformation if the strengths are set correctly (Piker, 2019). In some cases, it may not be necessary to reach a single energy minimum, as in creating a dynamic simulation such as a flag flapping in the wind. Typically, these tasks have been approached separately, requiring unique approaches. However, the Kangaroo Physics algorithm addresses these issues through a single energy minimization approach. The term “goals” encompasses constraints, applied loads, and elastic resistance as a more general term.

The Kangaroo Physics solver uses a specific algorithm known as dynamic relaxation (DR) to achieve energy minimization (Dasari et al. 2022). Developed by engineer Alistair Day in 1974 (Adriaenssens and Barnes, 2001), DR is a technique that finds equilibrium by combining all forces acting on each point and repeatedly moving all points through small steps until the forces balance and movement stops (Rezaiee-Pajand and Mohammadi-Khatami, 2018). This process occurs in a dynamic fashion, utilizing momentum, resulting in an oscillation about equilibrium, and damping is applied to remove energy and guarantee convergence (Chernyshev and Fominova, 2017). To gain a deeper understanding of DR, one can refer to the works of Mike Barnes (1999), who was a pioneer in applying its use for form-finding, particularly in tensile structures (Adriaenssens and Barnes, 2001).

In traditional engineering applications of DR, the desired outcome is simply the static equilibrium configuration (Siddiquee, Tanaka and Tatsuoka, 1995). Therefore, damping and mass values are chosen for stability and convergence rather than actual physical values. This does not impact the accuracy of the equilibrium solution, only the route and number of steps taken to reach it. As a result, it is sometimes referred to as pseudo-dynamics (da Silva, Breno and Rodrigues, 2006).

Since its version 2, Kangaroo Physics has not been using the traditional form of DR, but rather a new method where it combines projections onto the zero energy state of each goal instead of summing accelerations. Piker (2019) states that this approach was influenced by his conversations with the Computer Graphics and Geometry

Laboratory (LGG) group at the École Polytechnique Fédérale de Lausanne (EPFL) during the development of the paper "Projective Dynamics" (Bouaziz et al., 2014), although the method used in Kangaroo is slightly distinct from the one described in that paper and incorporates a unique approach to damping in order to speed up the convergence. Furthermore, it was later discovered that this method of combining projections can be considered as a type of the Alternating Direction Method of Multipliers (ADMM) (Piker, 2019).

ADMM is an optimization algorithm that is used to solve problems in the form of constrained optimization (Majzoobi, Lahouti and Shah-Mansouri, 2019). It is particularly useful for problems where the objective function is separable and the constraints are in the form of linear equations (Majzoobi and Lahouti, 2017). The algorithm is called alternating because it alternates between minimizing the objective function with respect to one variable while holding the others fixed, and then updating the values of the other variables (Yang and Zhang, 2009). ADMM can be seen as a generalization of the method of multipliers, which is a technique for solving constrained optimization problems (Adona, Gonçalves and Melo, 2017). It has been found to be effective in solving large-scale optimization problems, such as those that arise in machine learning and signal processing (Yang et al., 2013). There are several researchers who have made significant contributions to the development and advancement of the ADMM. Boyd et al. (2011) widely popularized the method and provided a comprehensive understanding of its theory, properties, and applications. Yang et al. (2022), who have done extensive research on the ADMM and its variants, have proposed several algorithms that improve its performance on certain types of problems. Banert et al. (2021) have done research on the ADMM and its variants, and have proposed several variants of the algorithm that improve its performance on certain types of problems.

It can be speculated that the ADMM algorithm is used to solve the problems of dynamic relaxation (DR) which is a numerical method for simulating the behavior of physical systems. In the case of Kangaroo Physics, instead of summing accelerations, this algorithm combines projections onto the zero-energy state of each goal which results in a more efficient and stable simulation (Piker, 2017). Additionally, Kangaroo Physics also incorporates a different approach to damping to accelerate convergence, which is not typically found in the classical ADMM algorithm (Zhang et al., 2019). In addition, the integration of ADMM in Kangaroo Physics provides a powerful tool for simulating the behavior of physical systems and can be used to fine-tune the behavior of the simulated physical system and optimize the parameters of the algorithm itself, such as the time step and the stiffness of the springs, to improve the accuracy and stability of the simulation (Piker, 2017).

Despite its advantages, Kangaroo Physics has also some limitations. One is that it operates on a discrete rather than a continuous level, and thus, the generated forms may not always be smooth or accurate (Piker, 2011). Additionally, the tool requires a high level of expertise to fully utilize its capabilities, and the simulation process can be computationally intensive (Piker, 2017).

The limitations can be summarized as follows:

- Complexity: Kangaroo Physics can simulate complex physical systems, but the complexity of the simulation can increase rapidly with the number of particles and constraints involved (Deuss et al., 2015).
- Stability: Kangaroo Physics uses a numerical method for simulating the behavior of physical systems similar to many other physics engines, which can be affected by errors such as round-off errors and instability caused by the choice of time step (Pilat, Suzuki, and Arita, 2012).
- Material properties: Kangaroo Physics is based on the particle spring system and DR, which is a simplified model of physical behavior. It does not take into account the material properties of the objects being simulated, similar to other physics engines (Baudet et al., 2009).
- Real-time simulation: Kangaroo Physics is not designed for real-time simulations, it is more suited for offline simulations and post-processing (Piker, 2013).

2.2.1.3. Applications

In the literature, there are many examples using Kangaroo Physics’ different modes of form-finding operations. The projects include concrete shell structures, bend-active membrane structures, funicular shell structures, and fabric formworks (Sunguroglu Hensel and Bover, 2013; Soriano et al., 2015; Mendez Echenagucia et al., 2019). The application areas of Kangaroo Physics in form-finding are diverse, ranging from architectural design and construction to product design, fashion, and even robotics (Piker, 2007; Piker et al., 2009; Bechthold, 2010). One of its key advantages is its ability to simulate the physical behavior of certain materials and structures, allowing for the optimization of form and geometry in relation to defined loads and material properties. Furthermore, Kangaroo Physics' algorithmic approach enables the exploration of a wide range of design options and variations, allowing for a more efficient and effective design process (Piker, 2007; Piker et al., 2009).

One of the real-life applications, Xtra Moenia, an installation built by SoftLab in San Gennaro North Gate, New York, USA, was designed by using Kangaroo Physics (Piker, 2013). By merging the two semicircular forms in a homogeneous manner, the overall form was constructed utilizing a minimal surface. In close collaboration with the structural engineering firm Arup, the final geometry was created. The entire installation is kept under tension by cables fastened to the nearby structures. Only when fixed at these particular locations and tensioned with the appropriate lengths would the shape, which is entirely site-specific, take on its real form. Since each component is unique, special software tools have to be created in order to create the installation.

Another example of using Kangaroo Physics for form-finding is the Nested Catenaries built by AHO Auxiliary Architectures Studio in Oslo in 2010 (Piker, 2013). The brick arch construction is the reversed hanging chain method that Antoni Gaudi developed in order to identify structures working only in compression. Physical and digital tests were conducted to produce the form. The study demonstrates that the nesting method can be used to develop distinctive features with high stiffness-to-weight under bending moments and is effective for load-bearing functions. This construction strategy makes it possible to form a spatial shell with the face-on laying of a single brick. Form-finding, computational modeling, Finite Element, and comparative analysis methods and tools were all used in the design and building prototypes (Sunguroglu Hensel and Bover, 2013).

Jukbuin Gridshell, designed by CODA BarcelonaTech in Barcelona, Spain, in 2012, is another example of the use of Kangaroo Physics in real-life applications (Piker, 2013). It is an experimental timber pavilion with a structural design inspired by traditional basketry and dynamic bending. To find an efficient shape, bending and gravitational forces were physically simulated in Kangaroo Physics (Soriano et al., 2015).

It is seen that the application of form-finding by using Kangaroo Physics involves tension-based cable, clay bricks, or timber structures, all of which are well-known and frequently used materials for construction. Although the above mentioned examples exploited Kangaroo Physics at its full potential, it is seen that the biobased materials are a missing material package in its library, thus, has a potential to further investigate.

2.2.1.4. Emerging materials

During the 17th and 18th centuries, developments and inventions in science and technology have increasingly affected every part of human life. From a socio-economic view, these developments have also been reflected as disrupted family life, harsh labor conditions, population growth, rapid production, rigidity in the social hierarchy, and so on (Lasi et al., 2014). These factors also influenced the built environment in such a way that concrete has started to dominate everyday life. Along with the fast-paced urban life, overconsumption and overpopulation have started to impact the Earth, as never seen before. The Earth's geology and ecosystems have been affected by the overwhelming human activity, bringing the Earth in danger with global warming and other changes in the environment, water, organisms, and the atmosphere (Risser and Goudie, 2018).

Especially over the last decade, those negative influences caused by humans have become unveiled at high rates and scales (Trenberth, 2018). Carbon dioxide emissions, global warming, ocean acidification, habitat destruction, extinction, and wide-scale natural resource extraction have been considered as signs that we have significantly modified our planet. Thus the era has started to be called Anthropocene, although some think that these changes do not represent enough evidence to declare a new formal geological epoch (Crutzen, 2012).

Scientists, researchers, and scholars have put forward the scope of human influence on Earth, entitling it as "Anthropocene" (Zalasiewicz et al., 2011). Marsh's work

“Man and nature: or, physical geography as modified by human action” (1864) is possibly the earliest research that discusses the anthropogenic global change. In addition, the term “Anthropozoic” was first coined by the geologist Antonio Stoppani in 1871, although the term was elaborated deeply in the 19th century by Arrhenius (1896) and Chamberlain (1897), focusing on carbon dioxide emissions and global warming. In the following years, Crutzen (2002) revived the concept of Anthropocene by referring to the current era as the era dominated by humans’ negative environmental impact.

In order to deal with these changes in the environment, design disciplines have started long ago to suggest material alternatives that are less harmful to nature. Although we cannot still observe common and grounded applications in the industry, the organizations, notably Material ConneXion, Materia, and Materiom have been developing databases for new types of materials and formulations in collaboration with external bodies such as academicians or organizations who are collaborating with nature.

Since novel types of materials and methods are still in development in terms of material formulation, analysis and manufacturing, all main and in-between processes are still open to development. It seems that the structural optimization and form-finding tools exist for conventional materials whereas novel types of biobased materials and composites have not been fully integrated yet. Therefore, it is important to review the processes of nature, as well as to co-design with organisms as potential collaborators in order to respond to challenges brought about by the Anthropocene, in addition to the natural and genetic algorithms, and the shared principles of natural and computer algorithms need to be further elaborated, since digital form-finding tools are heavily based on these principles and algorithms.

2.2.1.4.1. Architecture by Nature

Nature is capable of sustaining life with minimum resources and maximum performance (Oxman, 2012). There are strategies that nature utilizes to sustain life such as growth, response, action and reaction, evolution, mutation, adaptability or natural selection. As one of the results of these strategies, there appears maximum diversity with minimum inventory as Peter Pearce underlines in his book “Structure in nature is a strategy for design” (1981) from a biomechanical point of view.

In natural systems, there is a large amount of diversity of form. In morphological patterns of natural systems, there are also large amounts of forces that shape the forms such as geometrical, physical and chemical constraints (Oxman, 2007). For instance, snowflakes or crystals vary in their form because of different combinations of atomic arrays due to the changes in temperature that affects the density of the molecules although their molecular structures have exactly the same atoms and bonds; hydrogen and oxygen. As another case, a DNA molecule as a part of a biological system, demonstrates the same maximum diversity logic with minimum inventory, as each creature has a different array of DNA molecules although the atoms are the same.

As nature continuously evolves, each unique characteristic of biological materials and structures tends to adapt itself to the environmental conditions (Koch, Bhushan and Barthlott, 2009). For instance, lotus leaves have evolved to develop a self-cleaning feature (Forbes, 2008); strength of bone structure (Launey, Buehler and Ritchie, 2010); or color change (Kolle et al., 2010) and light absorption of butterfly wings (Han et al., 2012).

Evolutionary process, one of nature's crucial design methods to sustain life, was defined by Charles Darwin (1859) in "On the Origin of Species". All unique characteristics and abilities of species are rooted within the evolutionary processes. These processes involve growth, response, action and reaction, evolution, mutation, adaptability and natural selection. In this section, these natural algorithms based on mathematical functions are described.

Nature's mathematics is based on sustainability. As indicated before, nature sustains itself in an efficient way by consuming less and developing more for the vital functions for life. These generative systems found in nature have been simulated through distinct generative models in architecture. For instance, L-systems are employed in the design process to simulate botanic growth (Prusinkiewicz and Lindenmayer, 1990); cellular automata to simulate reproduction (Schiff, 2007); genetic algorithms to optimize the processes through fitness values; or swarm intelligence (agent-based) systems to simulate particle behavior through restricting particles within a given boundary (El-khaldi, 2007).

It is significant to note that these generative models are formalisms that simulate nature in digital environments; however, they already become an alternative source of knowledge to generate multifunctional surfaces or volumes with unlimited amounts of possibilities brought by natural materials with nature's own algorithms. In this manner, in the morphological search of evolution of structures in relation to natural forces, genetic algorithms are analyzed in order to see how structures develop in natural processes and adapt to environmental conditions as a way to inform human-made structures.

Genetic algorithms are closely linked to the term "morphogenesis" which is to describe the ways of bio-structural development of species in natural sciences which attracted architects and designers in terms of informing the design processes, resulting in much more efficient and durable outcomes (Reap, Baumeister, and Bras, 2005; Vincent, 2012; Vogel, 1998). For instance, a novel structural system was proposed through the biomechanical study of sea urchin's form (Kreig, 2012); and the studies on natural tissues led to the development of self-healing concrete systems (Ortega, 2000).

On top of such applications, in a nature-inspired morphogenesis approach, genetic algorithms have become instrumental in the projects that analyze natural growth, adaptation, reproduction and mutation. By analyzing genetic algorithms, architects and designers have moved beyond the inspiration towards soft robotics and nano-engineering for more effective applications involving self-assembling, self-evolving and programmable materials (Tibbits, 2012; Raviv, 2014). Since each species has unique characteristics, the morphogenetic development of each also differs accordingly. In other words, a plant's growth is different from an insect's growth in terms of morphological processes although the patterns within the processes are quite similar.

It's worth to mention that, these natural forms that evolved over time have become inspiring for design and engineering fields. Such as, biomimicry, the study of natural forms, processes, systems, and elements to solve human problems and create new designs (Benyus, 1997). However, in addition to the influence of nature on architecture, how architecture collaborates with the nature in order to develop novel methods and tools for a sustainable future needs a close attention.

2.2.1.4.2. Nature by Architecture

Life evolves out of the physical concentration of information, no matter if it is biological, artificial or architectural. Architecture started long ago to develop its natural environment that grounds the discipline onto an artificial and abstract expression of disconnected philosophical and ideological reflection of humanity (Salingaros and Mesden, 2006). However, under the forces of growing failure of humanity in terms of ecology, a new materiality has become a part of the debates which has the nature as the actual material at the center of its logic (Oxman, 2007).

> *"If you think of Brick, you say to Brick, 'What do you want, Brick?' And Brick says to you, 'I like an Arch.' And if you say to Brick, 'Look, arches are expensive, and I can use a concrete lintel over you. What do you think of that, Brick?' Brick says, 'I like an Arch"* (Kahn, 2003).

The Parthenon, the Eiffel Tower or the Golden Gate Bridge are all great examples of what is possible with a particular material. In these examples, the forms are the direct outputs of the material selection by necessarily taking material properties into consideration (Ashby and Johnson, 2014). However, during the last two decades, as happened in the Industrial age, not only what we design and manufacture; but also, how we design and manufacture have changed. While before the form was being influenced by the nature of material, today, with the advanced technology, nature of material can define the form. This new materiality approach utilizes several type of form-finding processes that allows designers to explore the nature of material; in other words, what a material wants to become.

Most of the information in the literature suggests that the materials have stayed in a secondary position compared to the form and function in design studies, although there is a great progress in material science. Recently, there are studies that elaborate on the material generation rather than material selection that was defined by Oxman (2010) as new materiality, which embraces the idea of material as the substance of form rather than progenitor of form.

While the understanding of materiality shifts from conventional materiality to new materiality, form generation also differs in each understanding. Form-making process is entirely contrasting to the process of form-finding. The omnipresence of computational tools has encouraged a culture of making in which if an object is able to be designed, then, it can also be built. In this conventional approach, material waste is higher compared to the outcome of form finding processes since form finding processes are as natural as the design problem (Oxman, 2007). An earlier example can be given from Frei Otto's physical form finding method in his work "Tensile structures: Cables, nets and membranes" (Otto and Glaeser, 1972) minimal surfaces with minimal nets were calculated through mathematical equations in an experimental setup. A similar approach is presented in the digital realm for this dissertation, considering the process as computational form finding in which material behavior and material performance is stimulated within the process.

Thompson in "On Growth and Form" (1942) advocates that each form of biological assets is informed by the phenomenon of growth. This progression of growth comprises the direct actions of distinct molecular forces and other compound processes in which the material is driven into the asset through incidental chemical, osmotic and other forces (Thompson, 1942). Besides, a direct relation between matter and energy, form and environment, organ and function in nature (Oxman, 2010). It is also important to note here that in nature, from a designerly perspective, the strategies and the mechanisms tend to distribute the material properties according to the functions during the form generation originated from an organically same protein sequence.

> *"…the chisel and gene, between machine and organism, between assembly and growth, between Henry Ford and Charles Darwin"* (Oxman, 2015).

On the other hand, contrasting to how nature grows, we assemble. In other words, if we consider what growth is to nature, then, fabrication is for design. In the late 18th century, the industrial revolution established the foundations for mass produced products based on an assembly line. However, form in nature is informed by the interaction of matter and energy where the material properties are distributed along the overall form as a single entity with varying material properties (Oxman, 2010). Therefore, it might be speculated that there are no joints in nature that originate after the pieces come into being. It might simply be considered as an indicator of how nature efficiently utilizes its resources in order to sustain a life. Therefore, while there are enhancements going on in the fabrication technologies, there is a need for redefining the field of digital design in the age of global warming and sustainability based on the new materiality approach regarding organic, degradable, renewable and recyclable biobased materials.

2.2.1.4.3. Classification of biobased materials

Beyond biomimicry or any other types of sustainability approaches, there is a huge vocabulary of bio-terms developed within the last decades ranging from biomorphism, biophilia, biodesign, biomaterials, bioart, to biomedicine and biochemistry. The terms are defined in different ways with regard to the discipline. The biodesign or biofabricated design terms were coined in design fields after the developments in medical fields, which refers to an umbrella under green chemistry research and developments around biobased product developments. Biodesign serves for a specific purpose by incorporating relatively narrower concepts such as biomimicry that looks into nature's form, organisms and processes and emulates it into design, or biophilia that visually copies nature for us to connect to it through emotional energy. Within the scope of biodesign, there are biobased materials and various composites used in the development of environmentally-friendly biodegradable products.

Since bio-terms co-exist in different literatures and make it harder to comprehend communication, it is necessary to create a framework through a classification on biobased materials and processes utilized in the design literature. In this dissertation, biobased materials were classified into three main categories based on their capability of metabolic activities and illustrated with examples of such materials (Figure 5).

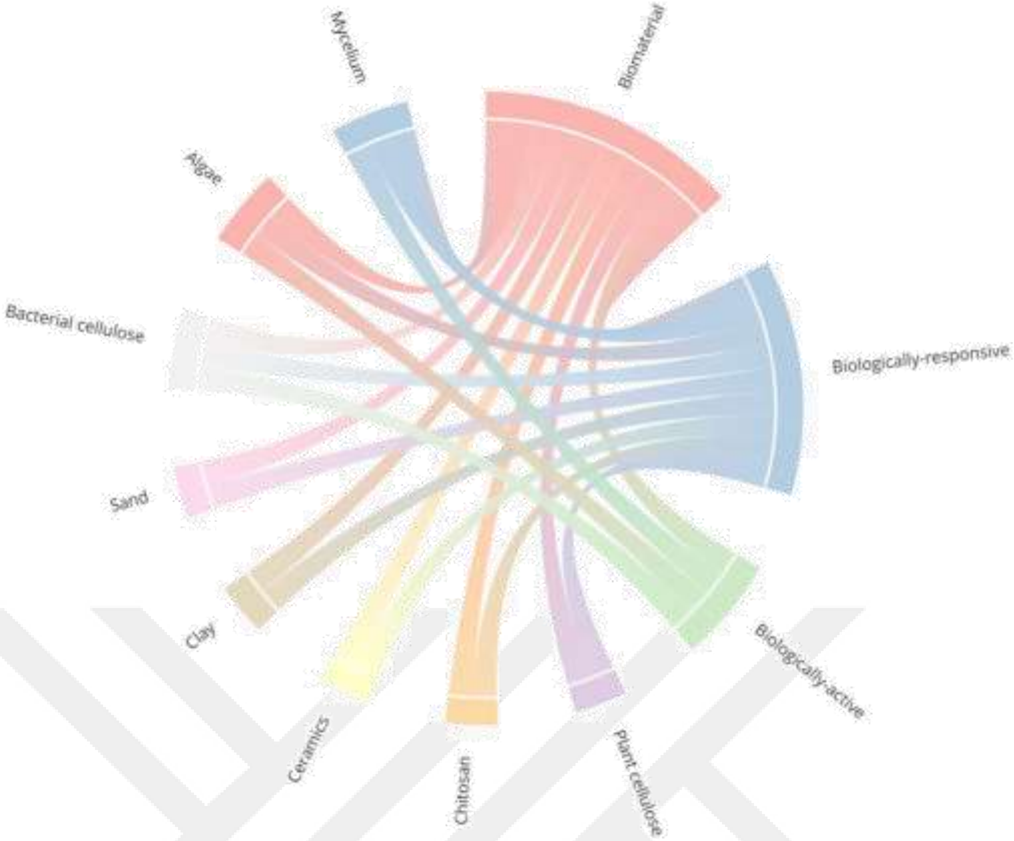

Figure 5. Proposed classification of biobased materials for design literature

As seen in Figure 5, in this dissertation, the biomaterials are relatively a larger list of biobased materials. The biologically-responsive materials also covers a larger portion. This figure illustrates the interrelationships of such materials based on their connections. For example, a biomaterial can also be biologically-responsive or biologically-active. On the other hand, biologically-responsive materials are not necessarily the biologically-active materials. A biologically-responsive material can be activated through heat or moisture, as well as enzymatic or biochemical catalyzers, although it cannot react against environmental forces without any intervention. For instance, thermoplastic polymers such as polylactic acid (PLA), polyvinyl alcohol (PVAL, PVOH) or *polyhydroxyalkanoates* (PHAs) can be created through polymerization under heat/evaporation, moisture, or through crosslinking (Xintao et al., 2001). These materials are biodegradable and they can be easily formed through molding or additive manufacturing. In this case, these polymers can be classified as a biomaterial, as well as a biologically-responsive material. However, since they are not a living organism with metabolism, they are not classified as biologically-active materials within the scope of this dissertation. The details regarding each type of materials are indicated below:

- **Biomaterials:** In the literature of medicine and medical engineering, the term biomaterial is defined as the materials that are engineered to interact with the living organisms for medical purposes (Park and Lakes, 1992). It means that a biomaterial can be composed of metals, ceramics, plastic or glass in combination with living tissues such as implants, biosensors or drug-delivery systems (Saltzman and Olbricht, 2002; Pérez-López and Merkoçi, 2011). Within the scope of this dissertation, the biomaterials are described as the materials that have biological roots; i.e., a part of a living organism or a material that is created by that living organism (Fernandez, 2006). Therefore, in this part, a review of the use of biomaterials with a specific focus on design literature and applications was conducted. These materials in these projects do not pose a risk for human health or the environment; instead, they are biodegradable, renewable, can be locally found, and available in the market.

The project Grow Bricks by BioMason realized in 2012 (Ednie-Brown, Burry and Burrow, 2013), used *Calcite-precipitating bacteria* that generates an enzyme for the removal of calcium carbonate, and for producing aggregates at room temperature. In order to produce bricks, first, the bacteria culture was mixed with sand and wet bio-cement. Then the mix was poured into the scaffolds. After the cultivation at room temperature for 4 days, calcium carbonate was deposited, and the bricks were tested for compression. It was seen that the changes in the growth process of bacteria affected the material properties of bricks (Hills et al., 2016). This idea of creating a bio-brick for the industry emerged out of the purpose of presenting an alternative to traditional masonry applications. Moreover, this process also achieves energy saving in two ways: Since the process is realized at room temperature, it eliminates burning fossil fuels. Another gain is that it removes the emission occurring during the operation of limestone.

The other project is Hy-fi pavilion by The Living, realized in 2014 (Benjamin, 2017). In this project, they used fungus which produces a network-based mycelium. It also converts agricultural waste into bricks. Agricultural waste mixed with fungi is taken from local farmers, and it is poured into scaffolds. After several days, as mycelium grows, fungi are eliminated by the addition of drying mixture. Although the output was a conventional brick, in this process, growth of mycelium enabled a regulation on material properties of the product such as strength, flexibility or water permeability.

There are also several more research projects that introduce different biomaterials for commercial products. Ecovative team engineered mycelium and mushrooms for packaging; Eric Klarenbeek is the first who fabricated mycelium through 3d printing in 2013; Mycoworks designed a leather bag with a similar process on mycelium.

As seen through given examples, biomaterials have a broad range of use such as product design, fashion design and architecture, and they are open to different fabrication methods. However, although these materials have common features such as being eco-friendly and biodegradable, and having biological roots, each differs in terms of their relationship with their surrounding environments, and ability to respond to external stimuli. It is important to classify these materials in such a way because they have their own parameters to survive, which should also be considered while working with these materials.

- **Biologically-responsive materials:** Biologically responsive materials are defined in medicine as the biomaterials that can adapt their material properties to the changing conditions of the outside environment through signals such as pH, toxins, temperatures, humidity or light (Kowalski et al., 2018). In parallel with this definition, biologically-responsive materials are defined as the smart biomaterials within the scope of this dissertation.

To illustrate, the HygroSkin project by Achim Menges at the Institute for Computational Design (ICD) is a work dealing with the composites consisting of wooden plates as biologically responsive materials (Krieg et al., 2014). Water is used as an agent that stimulates the size changes in wood fibers. When the wooden tissue absorbs water, the gap between fibers gets wider, and it affects the overall size as well. The pavilion responds to the changing humidity of the environment by mobilizing facade elements, therefore, this process does not require any effort in terms of energy efficiency. Computational tools were utilized in the fabrication process bringing a series of parameters into calculation such as direction of the fibers, ratio of length, width and thickness, form, and moisture level; in a way that the code mimics the material behavior (Menges and Reichert, 2012).

Another project is BioLogic by MIT Media Lab realized in 2015. The research team utilized *Bacillus Subtilis* which is dormant and inactive bacteria. The 0.2 mm silicone base was covered by a liquid cell culture, and the vapor was deposited to generate a composite membrane. In this process, the water was absorbed by the bacteria so that the surface bends (Yao et al., 2015) which provides elasticity to the silicone as a material property. In order to realize this process, a customized 3d printer that allows cells to be deposited on a thin fabric was built.

- **Biologically-active materials:** Biologically active materials are very central to this dissertation. There are differences from biomaterials and biologically responsive materials. For instance, biologically active materials can be manipulated by chemical or mechanical signals and they have a potential to impact their environments by biochemical and biomechanical changes (Kowalski et al., 2018). Therefore, there is a critical difference that the signals in the environment do not only cause a mechanical change but also activate other biochemical processes by consuming energy within the context of biologically active materials.

Solar leaf bioreactor facade, developed for BIQ House by the cooperation between Strategic Science Consult of Germany (SSC) and Colt International and Arup in 2013 (Wurm and Pauli, 2016), employs living algae. After the bioreactors are mounted to the facade, compressed air is run through breaks inside the panels in order to stimulate algae growth to provide insulation and to prevent heat loss within a loop system.

In this solar leaf bioreactor facade design, algae are used because of their capacity to absorb light. Depending on the density of cells, there is also a potential to design dynamic shading devices. If there is more light, more algae nurtures within the panels. In this project, this system can meet the heat demand of 5 residential units. These values can vary depending on the available daylight and scale of the projects.

Another example for the use of biologically active materials is the Bionic Leaf developed at Harvard Medical School, Pamela Silver Laboratory in 2017. The system is designed to reduce CO_2 deposition more than photosynthesis does through employing the *Ralstonia eutropha* bacteria. In overall, it is a composite system which involves inorganic and living systems where the bacteria consumes hydrogen and produces biomass and fuels. This project indicates the possibilities regarding the use of hybrid materials for the construction industry since it can be scaled accordingly. In natural conditions, most of the plants cannot go beyond 1% and algae cannot surpass 3% of CO_2 reduction competence; while the systems in which these algae are grown can reach up to 7% of efficacy in the short term (Zhang, Hammarstrom and Nocera, 2022).

There are various design strategies for the biologically active materials with regard to their components, functions and the flexibility to adapt to different environmental conditions. Predominantly, they are composed of compound composites that have strong mechanical properties although their unit cells or tissues are weaker (Ortiz and Boyce, 2008; Meyers et al., 2008). They consist of different cell compositions such as biopolymers like cellulose, keratin or collagen; or, minerals such as calcium carbonate or silica. Living organisms accumulate these constituents through a guided and feedback-based self-assembly process (Davies, 2013) at different scales such as molecular, cellular, and macro scales (Zolotovsky, 2017).

The major aspects of the below materials are that they are assembled in an organic way; they have multiple functionalities; and they can heal their damaged parts. For instance, as an example to self-assembly, in shell creation, soft tissues perform as a scaffold for the structure and as a protection against the outside environment while producing calcium to be crystallized to form the shell (Cartwright and Checa, 2007).

Minerals:

- Amorphous silica: calcareous spicules in sponges, diatoms, algae
- Calcium carbonate: shells such as reptile eggs, bird eggs
- Calcium phosphate: teeth, bones, horns
- Iron oxide (Magnetite-Fe_3O_4): teeth in chitons (marine worm), bacteria

Polysaccharides:

- Cellulose: walls of plant cells, bacteria
- Chitin: arthropods and insect exoskeletons

Proteins:

- Collagen: bone and dentine, tendons, muscles, blood vessels
- Elastin: skin, lungs, artery walls
- Keratin: bird beaks, horn, hair

As an example to another aspect, multi-functionality, the bone works as structural support, and at the same time it helps to generate blood cells for the body. Another example can be the trunks that support the trees in addition to the transfer of the nutrients. The skin of mammals provides temperature regulation, plus, it provides a protective barrier against the outside environment (Zolotovsky, 2017).

This material list can be extended further to explore different functionalities and potential applications in the field of architecture and design. Although biologically active materials cannot be replicated in practice through the use of synthetic materials since they lack such intricacy; they can be used directly for the design of the new materials.

Since these biologically active materials and tools have become reachable, the construction systems have also become more dynamic and emergent as seen in the properties of these materials and their morphogenetic processes. For instance, engineers and designers have been developing circuits that can identify signals and light within the cells and their communication environments (Yeh et al., 2007; Sprinzak et al., 2010; Xie et al., 2011; Park et al., 2014; Miki et al., 2015; Wamaitha et al., 2015; Guye et al., 2016). These signals enable cells to decide on their behaviors against other neighboring cells or environmental conditions. The inputs can alter the shape, behavior, function or mobility either within combinations or in sequences. The key intuition is that the assembly process is being realized in different scales within feedback-based loops (Davies, 2013).

In this manner, considering designing in collaboration with the biologically active materials, the processes demand a different series and scales of methods and applications that are far removed from conventional architectural design processes. Therefore, this indicates a shift in the design thinking process, in a way that the idea of borrowing or simply being inspired from nature needs to shift to the level of actually collaborating with living mechanisms found in nature by the help of emerging design and fabrication technologies.

There are many studies and responses regarding the ever-growing problem of sustainability which advocate that the key concept of genetics applied to architecture and design is the growth in order to address the sustainability issues (Estevez and Navarro, 2016). In terms of manufacturing designs as environmentally friendly products, there is a wide range of materials for digital fabrication technologies today, however, as a significant extension to the conventional material list, the potentials of biobased materials are currently under discussion as a potential solution to the environmental problems.

Digital fabrication technologies suggest a multifaceted ground for the production of customized products. The advantage of digital fabrication is not only providing the ability to realize rapid prototyping but also the ability to produce complex geometries, with a wide range of application areas from architecture to medicine (Studart, 2016).

Recently, with the developments in these technologies, the materials with intricate structures can be designed, which was not once possible with the conventional systems (Stampfl, Pettermann and Liska, 2011). These explorations are often inspired by the organisms found in nature, with complex architectures, since they are constantly being optimized according to the environmental conditions that surround them. These materials have multiple lengths, thicknesses, scales and properties that enable the organisms to adapt various environmental conditions through distinct processes such as adaptation, selection or self-healing (Studart, 2012). While developing such properties, there become a large archive of structural patterns observed in materials found in nature (Studart, 2016).

Some of these patterns can be mimicked through utilizing digital fabrication technologies, however, conventional processes of production become insufficient in many terms, especially when considering biologically active materials (Studart, 2012). Reversing this system, investigating the evolution of these microstructures in relation to natural forces is also a beneficial process to mimic natural patterns. There are many applications of biotechnology in various fields such as medicine or biofuel production as petroleum alternatives, industrial enzymes, plant sciences or design of biosensors etc. Biotechnology is a field involving a collaboration of different disciplines that enables the production of biological components or systems. Since the molecular transformations inside the cells can affect the organization, materiality and functionality of products (Green and Elisseeff, 2016), it has a great potential in terms of the use of biologically active materials in design; ranging from a single component to larger units.

As discussed earlier, taking the concept of growth as the key approach, one can think that there is a similarity between DNA and digital design. While DNA is a biological information chain, coded as 4 letters (A-T-G-C); artificial software creates a digital information chain, coded as ones and zeros. In this manner, a metaphor of referring to DNA as the biological software; and the software as the digital DNA, would not be wrong. The control of these information chains can lead to the emergence of form within biological and digital processes (bio-digital), which actually grow by the bio-digital self-organization systems, while the DNA and software are the new material; and while genetics and information technologies are the new systems and tools of bio-digital design (Estevez and Navarro, 2016).

To illustrate, Neri Oxman (2009) has carried out an experiment with a biopolymer chitin of shrimp shells, which gradually differs in concentration and strength in accordance with the places found on the body. She intended to craft an ecological material, and to imitate the variability property of chitin on shrimp shells. It becomes a biodegradable and environmentally friendly material which could potentially replace plastics in the near future. In the material-based computational design process, digital fabrication was combined with the biology and robotics in order to produce gradually varying material properties for a hydration and air-guided self-assembly (Oxman, 2009). The output is a heterogeneous material which was derived from chitin - a plentiful biodegradable polymer in the planet.

Another experiment conducted by Oxman (2015) is to design a life-sustaining cloth for interplanetary voyages. In order to achieve that, the design team intended to have bacteria which would flow in synthetically designed vessels within the clothes. They grow two distinct bacteria within the clothes: *Cyanobacteria* that live in oceans and transform light into sugar, and *Escherichia coli* that can be found in the human gut and digests sugar while releasing biofuel beneficial for the environment. She advocates that these two bacteria never meet in nature since one of them lives in the ocean and the other in the human body. Once the team 3D printed the artificial vessels of a wearable digestive system that spans 60 meters, they grew these bacteria on the human body in order to have varying material properties according to the desired functionality. While some parts are opaque, some other parts are slightly translucent – lighting up the body through photosynthesis (Oxman, 2015).

It is known that the potential of digital fabrication technologies to mimic structural aspects of living organisms lies in the system of production. Although there are technical similarities, man-made processes are still far from biological systems found in nature. However, there is a necessity to define and challenge the limits of digital fabrication of complex biological patterns, with biologically active materials, by developing approaches and methods for bio-digital fabrication.

Throughout the literature review, biomaterials, biologically responsive materials and biologically active materials were discussed through examples in order to get rid of conceptual confusions between three distinct definitions. The examples indicated the current applications for biobased material processes at the junction of architecture and biology. Some of the projects demonstrate the use of biomaterials only in fabrication processes. It is seen that the ability to respond to environmental changes is lost. Likewise, in the second group of projects, biologically responsive materials, although the material properties are incorporated into the design elements, cells' mechanical properties are being utilized instead of biochemical properties, and responsiveness is the final product. On the other hand, biologically active materials utilize biological functions of living organisms. Therefore, the overall system becomes capable of sensing the outside signals, and can actually interact with their environment by altering biological, chemical and mechanical properties (Kowalski et al., 2018).

Based on the examples found and reviewed in the literature, it is clear that there is a need for structural application of biobased materials and composites at different scales, although biomaterials, biologically responsive or active materials, have a potential for different scale applications.

2.3. Integrative proposal

After reviewing and classifying the biobased materials, it was observed that the methods and tools of manufacturing vary depending on the problems and goals. Although the materials are explored in a composite form in different ways, it can be deduced that there is a need for creating a computational form-finding framework to extend the conventional material list that are used in design and fabrication of prototypes in order to be able to respond to the challenges of Anthropocene through a more sustainable form of design and manufacturing.

2.3.1. Precedent studies of form-finding for biobased materials

In a study published in the "Journal of Cleaner Production" in 2018, the authors proposed the use of biobased materials, specifically straw bales, as an alternative to traditional building materials. They found that using straw bales as a building material can reduce the environmental impact of building construction and improve the energy efficiency of buildings (Tiwari and Shankar, 2018).

Another study published in the "Construction and Building Materials" in 2019, the authors proposed the use of biobased materials, specifically wood, as an alternative to traditional building materials. They found that using wood as a building material can reduce the environmental impact of building construction (Bai, Wei and Wang, 2019).

There is another one published in the "Renewable and Sustainable Energy Reviews" in 2020, the authors proposed the use of biobased materials, specifically bamboo, as an alternative to traditional building materials. They found that using bamboo as a building material can reduce the environmental impact of building construction and improve the structural performance of buildings. They also highlighted the potential of bamboo as a material for energy-efficient construction and its positive impact on indoor environment quality (Jiang, Li and He, 2020).

In a study published in "Sustainability" in 2020, the authors proposed the use of biobased materials, specifically flax fibers, as an alternative to traditional building materials. They found that using flax fibers as a building material can reduce the environmental impact of building construction and improve the mechanical performance of buildings. They also highlighted the potential of flax fibers as a material for sustainable and energy-efficient construction (Kan, 2020).

A study published in "Materials Today Sustainability" in 2020, the authors proposed the use of biobased materials, specifically mycelium (a vegetative part of fungi), as an alternative to traditional building materials. They found that using mycelium as a building material can reduce the environmental impact of building construction, it is renewable and biodegradable, and the mechanical and thermal properties are suitable for insulation, sound dampening, and structural applications (Alvarado and Gaydos, 2020).

A study, published in the "Journal of Materials Research and Technology" in 2020 by Biswas, Panda, and Kar, used a computational form-finding process to design structures made of biobased materials, specifically bamboo. They used a multi-objective optimization approach based on genetic algorithm to optimize the design of a truss system made of bamboo and found that their method was able to produce efficient and stable structures (Biswas, Panda and Kar, 2020).

In another study, published in the "Construction and Building Materials" in 2021, the authors proposed a computational form-finding process to optimize the design of a beam-column system made of natural fibers. They used a genetic algorithm to optimize the design of a beam-column system made of natural fibers, such as jute, hemp, and flax. They showed that the optimized design was able to improve the strength and stiffness of the structure (Zhang, Li and He, 2021).

Another example published in "Sustainable Cities and Society" in 2020, the authors used a computational form-finding process to design a structural system made of biocomposite materials. They used a multi-objective optimization approach based on the particle swarm optimization to optimize the design of a truss system made of biocomposite materials and showed that the optimized design was able to produce a more efficient structure with less material (Gao, He and Liu, 2020).

In a study published in "Materials Today Communications" in 2020, the authors proposed a computational form-finding process to design structures made of biobased materials, specifically bamboo. They used a topology optimization approach to optimize the design of a plate system made of bamboo and found that their method was able to produce efficient and stable structures that met specific design criteria (Zhang, He and Liu, 2020).

A study published in "Renewable Energy" in 2020, the authors proposed a computational form-finding process to optimize the conceptual design of a wind turbine blade made of natural fibers. They used a multi-objective optimization algorithm based on the particle swarm optimization to optimize the design of a wind turbine blade and found that the optimized design was able to produce a more efficient structure with less material (Wang, Li and He, 2020).

The studies that were mentioned above, all have in common the use of biobased materials, such as bamboo, wood, natural fibers, straw bales, or mycelium (vegetative part of fungi), as an alternative to traditional building materials, such as concrete and steel. These studies have investigated the potential benefits of using these materials in architectural design and construction in terms of sustainability, environmental impact, energy efficiency, structural performance and indoor environment quality. Another common point is that all the studies propose an alternative that is more sustainable and environmentally friendly to traditional building materials that are often associated with high emissions of carbon and other pollutants and non-renewable resources. Another common point is the focus on the structural performance and mechanical properties of the materials to be used in construction and design, to ensure the safety and durability of the building, as well as the thermal insulation and energy efficiency. Lastly, all studies suggested that the biobased materials have a positive impact on indoor environment quality by providing better air and sound quality, and being less toxic than some traditional building materials.

One possible thing that is missing in all the studies is a detailed cost analysis of using biobased materials in comparison to traditional building materials. While many of these studies have shown the environmental and sustainability benefits of using biobased materials, it is also important to consider the economic feasibility of these materials in practice. Additionally, while some studies proposed the use of specific biobased materials and focus on their environmental or structural performance, it might be helpful to have a more in-depth comparison of different biobased materials, in terms of their material composition, environmental impact of the process and cost, to identify the most suitable materials for different scale applications. Another missing aspect in the studies might be a lack of discussion of the scalability and availability of these materials, in order to determine whether or not they are widely available and can be used on a large scale in construction. Lastly, although some studies mention the impact of using biobased materials on indoor environment quality, more research is needed to fully understand how these materials affects the thermal comfort or the acoustic performance, especially in long-term periods, and to define the limits of use of certain types of biobased materials.

The table in relation to the tools, methods, materials, form-finding methods, software and the goals of above mentioned recent research examples from the literature are shown in Table 2 below.

Table 2. Form-finding approaches used for biobased materials

Research	**Materials**	**Form-finding approach**	**Software**	**Goal**
Tiwari and Shankar (2018)	Straw bales	Driven by context	Ladybug	reduce the environmental impact of building construction and improve the energy efficiency
Tiwari and Shankar (2018)	Straw bales	Driven by context	Ladybug	reduce the environmental impact of building construction and improve the energy efficiency
Bai, Wei, and Wang (2019)	Wood	Driven by context	Ladybug	reduce the environmental impact of building construction
Jiang, Li, and He (2020)	Bamboo	Multi-objective	Karamba 3D	impact on indoor environment quality
Alvarado and Gaydos (2020)	Mycelium	Performance-based	Galapagos	improve insulation and sound dampening
Kan (2020)	Flax fibres	Formation-based	Kangaroo	energy-efficient construction
Biswas, Panda, and Kar (2020)	Bamboo	Multi-objective	Karamba 3D	optimize the design of a truss system

Table 2 (continued)

Gao, He, and Liu (2020)	Natural fibers	Multi-objective	Silvereye	optimize the design of a truss system by particle swarm optimization
Wang, Li, and He (2020)	Natural fibers	Multi-objective	Karamba 3D	optimize the design of a wind turbine blade
Zhang, He, and Liu (2020)	Bamboo	Topological	Galapagos	optimize the design of a plate system
Zhang, Li, and He (2021)	Natural fibers	Topological	Galapagos	optimize the design of a beam-column system

The examples show that although various biobased materials were explored in the literature as structural materials such as wood, bamboo, natural fibers or mycelium, their structural performance in relation the form was not investigated. Instead, their environmental analysis were conducted for improved thermal insulation, reduction of material usage or environmental impacts. In addition, although biobased materials were explored in different scales, there is no performance-based form-finding studies for biologically active materials for structural use in particular.

After reviewing the literature, as a case study, Bacterial cellulose (BC), a microbial polysaccharide, have found to be a proper source of knowledge and a morphogenetic model for structural applications due to its material properties such as its structural integrity, hydrophilic nature and biodegradability (Fernandez, 2006; Mohite et al., 2014) although the use of bacterial cellulose as a biologically active material for a structural application is still in its infancy and has no prior applications.

Considering the limitations with the Kangaroo Physics in terms of specific biobased material or composite integration, BC was investigated in terms of its growth, material properties and behavior, as well as industrial production and composite explorations. The integration of such information into computational form-finding process was proposed in the following chapters through tensile testing and computational validation.

2.3.2. Tensile testing procedures for biobased materials

Tensile testing is a method used in materials science and engineering to determine the mechanical properties of a material, such as its strength, elasticity, ductility, or toughness (Chen et al., 2020; Rokhlin et al., 2019; Xiong et al., 2018). The method involves applying a gradually increasing tensile load to a specimen of the material and measuring the resulting deformation and failure (Chen et al., 2020). The test is typically conducted at a constant strain rate, with the load and deformation data recorded throughout the test (Rokhlin et al., 2019). Tensile testing can be performed on a wide range of materials, including metals, plastics, composites, ceramics, and biologics (Xiong et al., 2018). Standards for tensile testing have been developed by organizations such as ASTM International, ISO, and DIN, which provide guidelines for specimen preparation, testing conditions, and the reporting of test results (ASTM International, 2018; ISO, 1993; DIN EN, 2001). The standards are commonly defined in the following format: ASTM E8/E8M-11a, ISO 527-2:1993, and DIN EN ISO 527-1:2018-12. There are several methods for tensile testing, including the standard tensile test, the non-destructive tensile test, reduced section tensile test, the sub-size tensile test, the high-temperature tensile test, and the low-cycle fatigue tensile test. The choice of method depends on the specific material and the information desired from the test.

In recent years, tensile testing has been widely applied to biomedical materials and particularly to soft tissues like ligaments and tendons, where it has been used to study the mechanical properties of these materials, such as their strength and elasticity. A study published in the Journal of Biomechanical Engineering in 2020 by Chen et al., showed how tensile testing can be used to study the effect of aging on the mechanical properties of tendons, by comparing the properties of tendons from young and old individuals. Another study published in the Journal of Applied Biomechanics in 2019 by Rokhlin et al., explored how tensile testing can be used to evaluate the mechanical properties of ligaments and tendons in a non-destructive and repeatable manner. Both studies used tensile testing as a key method to investigate the mechanical properties of biological soft tissues, and they reported that the method can provide useful insights into the behavior of these materials under different loading conditions, such as aging or disease.

In the field of polymeric materials, tensile testing is widely applied to evaluate the properties of plastics and composites. A study published in the Journal of Polymer Engineering in 2018 by Xiong et al., used tensile testing to investigate the effect of filler content and size on the mechanical properties of polymeric composites. The study found that as the filler content and size increased, the mechanical properties of the composite improved. Another study published in the Journal of Materials Science in 2019 by Smith, used tensile testing to evaluate the effect of temperature on the mechanical properties of a thermoplastic polymer. The study reported that as the temperature increased, the strength and ductility of the polymer decreased.

In conclusion, tensile testing is a widely used method in materials science and engineering to determine the mechanical properties of a material. It can be applied to a wide range of materials, including metals, plastics, composites, ceramics, and biological soft tissues. Standards for tensile testing have been developed by various organizations, and several methods are available to suit different materials and test requirements. Tensile testing has been widely used in recent years in the field of biomedical materials, polymeric materials, and many others, to investigate the mechanical properties of these materials under different conditions.

Within the context of this dissertation, it is seen that the tensile testing can be conducted on BC biofilms and composites using a similar approach to that used for similar materials with similar behavior, with some modifications to account for the unique properties of these materials. BC is a biologically active material and it is important to ensure that the test conditions do not affect the biological activity of the material, such as by controlling the temperature, humidity, and other environmental factors. In addition, the test specimens should be prepared under aseptic conditions to avoid contamination.

Standards that can be used as guidelines for tensile testing of BC biofilms and composites include ISO 527-2, ISO 37, DIN EN ISO 527, ASTM D638 and ASTM D882, which provide guidance on specimen preparation, testing conditions, and the reporting of test results (ISO, 1993; DIN EN, 2001; ASTM International, 2015; DIN EN ISO, 2018).

- ISO 527-2:1993 "Plastics -- Determination of tensile properties -- Part 2: Test conditions for films and thin sheeting" is a standard that provides a method for determining the tensile properties of plastic films and thin sheeting, including the determination of tensile strength, elongation at break and modulus of elasticity.
- ISO 37:2010 "Rubber, vulcanized or thermoplastic -- Determination of tensile stress-strain properties" is a standard that provides a method for determining the tensile properties of rubber and thermoplastic materials, including the determination of tensile strength, elongation at break, and modulus of elasticity.
- ASTM D638 "Standard Test Method for Tensile Properties of Plastics" is a standard that provides a method for determining the tensile properties of plastics, including the determination of tensile strength, elongation at break, and modulus of elasticity.
- ASTM D882-18 "Standard Test Method for Tensile Properties of Thin Plastic Sheeting" is a standard that provides a method for determining the tensile properties of thin plastic sheeting, including the determination of tensile strength, elongation at break, and modulus of elasticity. It is similar to ASTM D638 but it is specifically tailored for thin sheeting.

However, it is important to note that these standards are not specifically developed for BC and may not fully capture the behavior of this material. Therefore, it is necessary to adapt or modify the test methods to suit the characteristics of BC. One of the challenges of tensile testing of BC biofilms and composites is that it is a very sensitive material, and it can be damaged or modified by the testing conditions. Although the tensile test here is destructive, it is important to be careful when handling, preparing, and testing the specimens to avoid damaging the material and to ensure that the test results are accurate and reliable. Additionally, the mechanical properties of BC can vary depending on the strain of bacteria used, growth conditions and the environment. Therefore, it is important to consider these factors and control them to get consistent results.

2.3.3. Discussion on the mechanical-computational integration

Testing the tensile properties of bacterial cellulose can be a challenging task due to its unique properties as a biologically active material. However, various methods could be adapted from the literature to test the tensile properties of BC.

One common method is to use a universal testing machine (UTM) to apply a tensile load to the bacterial cellulose samples, while measuring the applied load and the corresponding displacement or strain. The tensile properties, such as tensile strength, Young's modulus, and elongation at break can then be calculated from the load-displacement data. Another method that has been proposed in the literature is to use a nano-indentation technique, where a small indenter is used to apply a small load to a small area of the bacterial cellulose sample, and the resulting displacement is measured. The tensile properties can then be calculated from the load-displacement data.

Material integration into the physics engine of the Kangaroo has been an active area of research in recent years. The physics engine, which is based on the particle spring system (PSS), has been used to simulate a wide range of physical phenomena, including cloth, soft bodies, and rigid bodies. One approach to material integration is to incorporate material properties, such as Young's modulus and Poisson's ratio, into the simulation.

Daniel Piker's "Kangaroo: Form Finding with Computational Physics" is one of the significant source as a journal article published in 2013 that provides an introduction to using the Kangaroo Physics engine to perform form-finding simulations. The article covers the basic principles of the particle spring system (PSS), which is the foundation of the Kangaroo Physics engine, as well as advanced topics such as material properties, nonlinear behavior, and optimization. The article is written in a tutorial style and includes step-by-step instructions and examples that demonstrate how to use the Kangaroo Physics to simulate a wide range of physical phenomena, including cloth, soft bodies, and rigid bodies. It also includes a number of case studies that illustrate the use of Kangaroo in different design contexts, such as architectural design, product design, and fashion design. Additionally, Piker explains how to use the Kangaroo Physics to perform form-finding simulations, which is a technique used to explore the structural and visual properties of a design. Form-finding simulations allow to explore the behavior of a design under different loading conditions and to identify the most efficient and stable configurations (Piker, 2013). Overall, it is a valuable resource for the designers, architects, engineers, and researchers who want to learn how to use Kangaroo to perform form-finding simulations and create realistic physical simulations.

In a study by Liu et al. (2013), a material model was developed that takes into account the anisotropy of the material and the effect of strain rate on the deformation. The model was implemented in Kangaroo Physics and was able to accurately simulate the deformation of fabrics.

Another approach is to use machine learning techniques to model the material properties. In a study by Zhang et al. (2017), a neural network was trained to predict the behavior of a cloth material under different loading conditions. The trained model was then incorporated into Kangaroo Physics and was able to simulate the deformation of the cloth in a realistic manner.

In addition to incorporating material properties into the simulation, the researchers have also explored methods for capturing the behavior of materials under different loading conditions. For example, in a study by Kim and Shin (2018), a method was proposed for capturing the nonlinear behavior of materials using a reduced-order model. The method was tested on a variety of materials, including rubber and metal, and was able to accurately capture the nonlinear behavior of the materials.

Overall, the integration of material properties and behavior into the Kangaroo Physics has the potential to improve the credibility of simulations and enable the simulation of a wider range of physical phenomena. However, novel type of biobased materials or composites are not listed or currently cannot be incorporated unless their material properties are introduced. Within the context of this dissertation, once the tensile properties of bacterial cellulose (BC) are obtained, they can be integrated into computational form-finding by using customized components. The advantage is that it allows for the simulation of physical systems, such as those involving tension and compression. By inputting the tensile properties of the BC, such as the Young's modulus and tensile strength, into the Kangaroo Physics, it is possible to simulate the behavior of the material under different loading conditions and predict its deformation and failure. This manipulation can be useful in designing structures or products that use BC or any other biobased materials and composites.

CHAPTER 3: A FRAMEWORK FOR THE MECHANICALLY-INFORMED COMPUTATIONAL FORM-FINDING FOR BIOBASED MATERIALS

The workflow within this dissertation is experimental in such a way that it presents findings for computational and mechanical form-finding processes by suggesting a framework through the case of bacterial cellulose (BC) and its composites as an unconventional, biobased, and a biologically active material for design. The main focus is to simulate the material behavior of such biocomposites as precisely as possible in a digital platform in order to open up a discussion on the possibility of real-life constructions based on the load-bearing biodegradable materials and on enhancing the digital form-finding processes by extending the current material list.

3.1. Experiment design and methodology

The dissertation is based on quantitative data where the systematic approach is divided into three main stages (Figure 6): *Acetobacter Xylinum (A. xylinum)* growth and composite material design; measuring material properties through tensile testing; and mechanically-informed computational form-finding.

Within the context of this dissertation, biobased materials as an extension to the existing material list for digital form-finding tools were explored through the case of bacterial cellulose (BC) due to its advantage of strong fiber composition, and therefore, due to the potential of being a structural component in design practices.

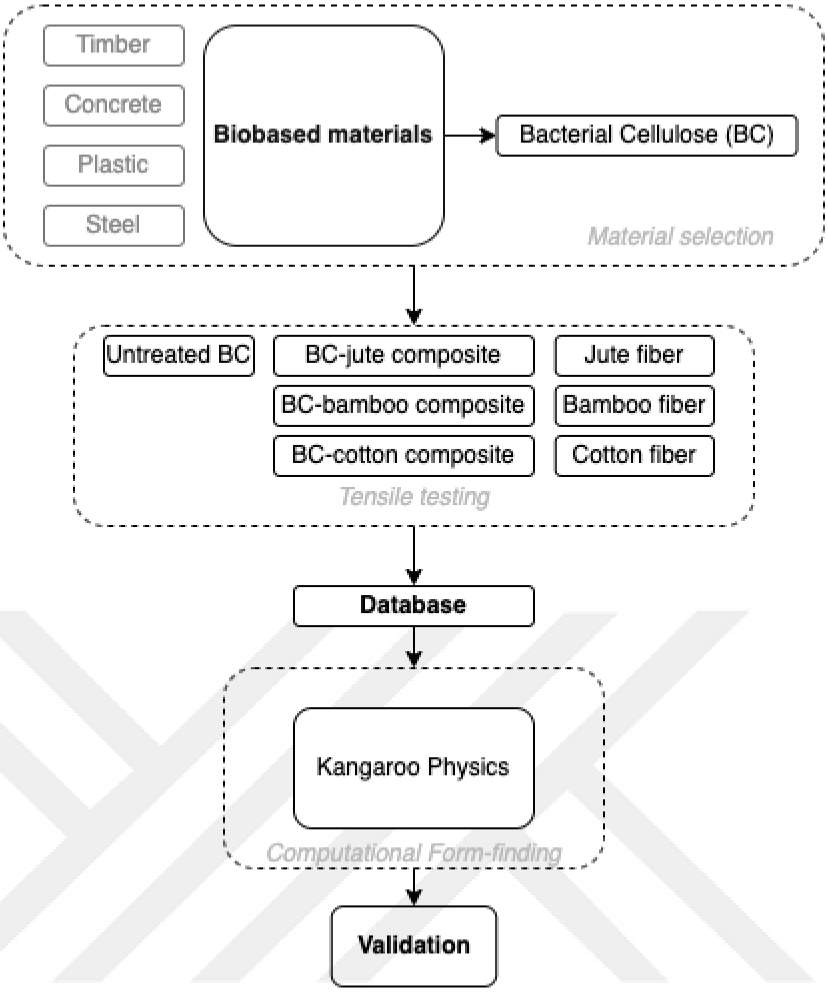

Figure 6. Methodology: Material selection, tensile testing, computational form-finding

Besides the BC biofilm, plant cellulose fibers were also investigated in order to provide reinforcement and to further increase the strength of composites. The mechanical properties of BC, especially the tensile strength, is provided by the biomechanical functions of bacteria cells where the BC becomes facially attached to the plant cellulose fibers. It was envisioned to design a biocomposite system that can be further engineered with a specific focus on load-bearing materials.

In order to do so, this chapter focuses on the morphogenetic properties of BC and environmental factors on its behavior, as well as its digital and mechanical form-finding processes through the Grasshopper/Kangaroo Physics. The overall process includes early experiments to get to know about the nature of BC, its behavior in relation to environmental and physical conditions, its adhesion capacity on natural fibers, and the tests on its strength under the tension forces through the form of a catenary geometry.

The curve which an idealized hanging chain or cable acquires under its own weight if supported solely at its corners in a homogeneous gravitational field is known as a catenary in physics and geometry (Handy, 2011). The catenary curve resembles a U and appears to be an arch with a parabolic form, however it is not a parabola. In materials science, the catenary is also known as the alysoid, chainette, or funicular. (Kim and Kim, 2013). Catenaries are also described by rope statics in a traditional statics scenario with a hanging rope (Handy, 2011).

Robert Hooke is credited with using the catenary geometry in the construction of arches, referring to it in the context of the reconstruction of St. Paul's Cathedral has a "true mathematical and mechanical form" (Ginovart et al., 2017). The Arch of Taq-i Kisra at Ctesiphon is one of several much earlier arches that resemble catenaries (Motamed and Rückert, 2015). In 1744, Euler made the claim that the catenary is the curve that, when rotated around the x-axis, produces the surface with the smallest surface area for the specified bounding circles (the catenoid) (Colding and Minicozzi, 2006). In 1796, Nicolas Fuss provided equations outlining how a chain would balance under any force (Foster and Tim, 2016).

Since the catenaries work great in tension and are expected to work well under compression, in this dissertation, catenary geometries were used to simulate the behavior of bacterial cellulose-based geometries.

3.2. Bacterial Cellulose (BC)

There are a number of motivations to use *Acetobacter xylinum* (*A. xylinum)* bacteria as a biologically active material. For instance, it is known that it can stay active and can be attached into a 3D network that cellulose fibers create (Derme, Mitterberger, and Di Tanna, 2016). Since this bacteria is a single cell organism that adapts itself to the changes in the environment such as temperature, humidity or sugar levels, it can be further engineered in order to allocate various functions as desired. Due to its high water content, it can sustain the system for long durations (Backdahl et al., 2006). Another reason for using this bacteria is that it can be rapidly grown into desired form through guidance. This has been very critical to fashion and product designers since they are very much attracted to it due its rapid growth. Moreover, cellulose, in general, as an environmentally friendly material, has a high demand to replace petroleum-based products (Huang et al., 2014).

3.2.1. Material properties and behavior

The bacterial cellulose (BC), a polysaccharide polymer, by its nature, has a high water capacity, high crystallinity, ultrafine fiber networks (20-100nm), high purity, high tensile strength and 15-35 GPa of Young's modulus (Lin et al., 2013; Huang et al., 2014). The nanofibril structure of bacterial cellulose provides high tensile strength which opens up its potential for structural use. It is also free of toxic molecules, such as pectin, lignin or hemicelluloses (Huang et al., 2014).

The environmental factors also have a huge amount of impact on the regeneration time. In the literature, it is seen that some bacteria populations could live far from Earth's surface, while some other types could only reproduce themselves once in a thousand years (Lin et al., 2013; Huang et al., 2014). Therefore, growth rate also depends on the growth medium where bacteria find energy source and optimum conditions.

The BC is a type of cellulose that is produced by bacteria, having richer material properties compared to regularly used plant cellulose in the industry (Bajaj et al., 2009). The focus of the dissertation is to grow a structure assembled by *A. xylinum* bacteria, attached and integrated into a plant cellulose reinforcement. The bacteria cells need a certain quality of environment to survive. This bacteria can be found in sugar-rich liquids where it transforms sugar molecules into cellulose. This chain of cellulose formation has a great potential for self-assembly within a defined scaffold area.

As indicated above, BC requires certain environmental conditions. In addition to these prerequisites, carbon and nitrogen sources in the environment are significant. In recent years, various carbon sources including monosaccharides, oligosaccharides, alcohols, sugar alcohols and organic acids, have been used to maximize bacterial cellulose production by various *A. Xylinum* strains (Ishihara et al., 2002; Keshk and Sameshima, 2005; Masaoka et al., 1993; Matsuoka et al., 1996). The studies show that the highest yield of production is provided by glycerol, followed by glucose, fructose, inositol and saccharose. The efficiency of glycerol is explained by the ratio of consumption and production which is 45.4% while the growth rate is 97% for glucose (Mikkelsen et al., 2009; Yang et al., 1998). In addition, it is stated that galactose is not an efficient source of carbon for bacterial cellulose production (Akoglu et al., 2010). Another material property, the crystallinity, can also be enhanced by the presence of glucose and fructose, compared to other carbon resources (Keshk and Sameshima, 2005).

The material properties of bacterial cellulose are also affected by oxygen, pH and temperature levels in the environment. The optimum pH value changes between 4 to 7; temperature 28-30ºC although it is observed that some cultures obtained from fruits could form a thick polysaccharide between 37-40ºC (Akoglu et al., 2010).

Temperature changes under still and agitated culture conditions also affect polysaccharide production differently. In agitated culture, polysaccharide production at 30°C was higher than 37°C, while the change in temperature in still culture does not cause any change in polysaccharide production (Keshk and Sameshima, 2005). It is also seen that the BC production rate is linked to the oxygen transfer rate. The highest efficiency is seen at 10% oxygen saturation in the still fed culture (Akoglu et al., 2010). The control of pH and oxygen level are critical in efficiency.

In conventional fermentors, cellulose production becomes a viscous medium, the ventilation becomes inadequate, and it affects cellulose production (Akoglu et al., 2010). In addition to regulating environmental conditions such as the optimum temperature, oxygen and pH to which bacteria will develop into, the presence of acetic acid also affects the cellulose production. It is reported that the addition of acetic acid increases the water holding capacity of cellulose (Akoglu et al., 2010). In addition, the increase in the amount of CO_2 and pressure in the environment disables cell development and decreases cellulose production.

3.2.2. Industrial production

More recently, new areas of application of bacterial cellulose have emerged due to its potential integration of optical properties, conductivity, or magnetism. (Iguchi et al., 2000; Hu et al., 2011; Wanichapichart et al., 2012). It has been discussed in the literature that since bacterial cellulose has a unique nanofibril network organization, its potentials to be utilized as a scaffold for various applications such as tissue engineering; or as diaphragms for speakers when it is dried; food packaging or reinforcing the silk fabrics are already proven (Wu et al., 2012; Huang et al., 2014).

Recently, bio-fabrication and scaffolding methods for the observation and control of the morphology of 3D bacterial cellulose membranes were developed (Derme, Mitterberger and Di Tanna, 2016). The team suggested and applied a self-assembly fabrication method in order to provide a scaffold and a 3D space as a target geometry. They employed different growth patterns and particle spring systems to simulate its behavior under tension forces. The team concluded the research with several valuable outputs. According to the research, the BC can be formally manipulated during cultivation since it’s moldable in wet conditions; be grown onto any target geometry with various dimensions; be preferentially grown on the natural fibers such as sisal for reinforcement.

Although the above mentioned research might be the first steps of a novel application method, there is not any optimization software or components for biobased materials and composites in particular. Therefore, there is still a need for a comprehensive analysis on the BC in order to understand its material properties with a mechanical validation to be able to inform the digital design processes. It also seems that the applications still remain at a rather small scale. Within the scope of this dissertation, load-bearing capacity of bacterial cellulose as a biobased material is explored through form-finding and mechanical testing processes by validating the structural performance.

3.2.3. Biofilm growth

The preference of BC lies in the amount of the existing empirical knowledge regarding its fiber configuration. It is a proven fact that the nanofibril structure of bacterial cellulose provides high tensile strength (Huang et al., 2014). However, the literature lacks the extent of that knowledge in potential design applications in terms of its structural use. Therefore, early exploration studies were conducted in order to explore and experiment on its potential for structural use in design applications.

In general, bacterial growth is defined as a rise in the number of bacteria within the culture rather than the dimensions of each cell. The bacterial growth happens in two ways: Geometric or exponential. In the latter, there are division cycles throughout the generation process where a single cell divides itself into two identical cells. These two cells are again divided into four, then eight, then sixteen and so on (Huang et al., 2014).

The generation time depends on the nature of bacteria. While some of the bacteria quickly regenerates itself such as *Clostridium perfringens* completing a generation cycle in 10 minutes, or *Escherichia coli* being doubled within 20 minutes; regeneration takes more time for some of the bacteria such as *Mycobacterium tuberculosis*, between 12-16 hours (Lin et al., 2013).

Within the early explorations, first, the nature of BC was explored through several observations. The culture used in the process of fermentation and production was *Acetobacter Xylinum (A. xylinum)*. The production of BC (Figure 37) took place within 1 L. of water, added with 4 gr. of green tea that was infused for 10 minutes. at 100°C, 100 gr. of sucrose and together with the 30 ml. of fermented liquid for acidification at 20 ± 2 °C and 65 ± 5% moisture in static conditions for 34 days. After 34 days of cultivation, the biofilm on the surface of the container was removed. For the pretreatment, the biofilm was placed with an alkalic solution to detach the residue of the growing medium for 8 hours. At the end of the 1st, 2nd and 4th hours, the solution was refreshed. The culture was sterilized at 121°C for 15 minutes with the use of an autoclave machinery. The biofilm was sliced apart to be used as inoculum in the subsequent fermentations for another 34 days. The procedure was adapted from the research conducted by De Filippis et al. (2018) and Sederaviciüte, Domskiene and Baltina (2019).

Figure 7. Bacterial cellulose production (Source: Filippis et al., 2018; Sederaviciüte, Domskiene and Baltina, 2019)

The material properties were interpreted visually in terms of rigidity, flexural capacity during dehydration, thus workability for further experimentations (Figure 8). It was observed that the isolated BC had strong tension capacity in wet conditions, while its tensile strength was reduced in dry conditions (Figure 9) which validated the literature findings. Images provided by an electronic magnifier at x500 were provided in Figure 10-11. It can also be deduced that the homogeneity of surface quality also decreases as it dries.

Figure 8. Bacterial cellulose biofilm (49,2% moisture)

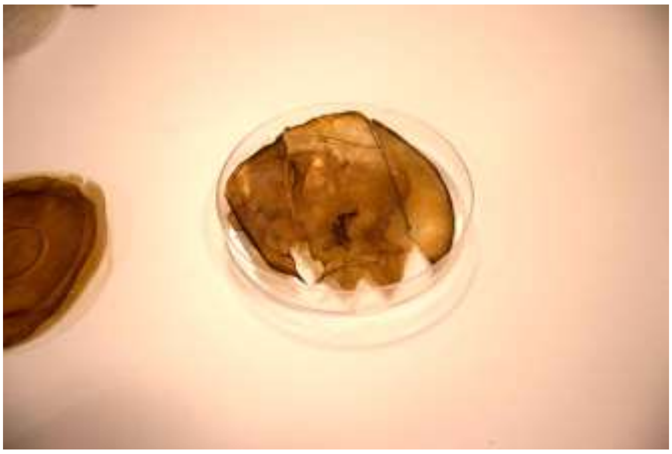

Figure 9. Dehydrated bacterial cellulose biofilm (0% moisture), cracked under tension

Figure 10. Bacterial cellulose biofilm (49,2% moisture) x500

Figure 11. Dehydrated bacterial cellulose biofilm (0% moisture), cracked under tension x500

3.3. Composite explorations

The composite materials have received a significant amount of interest from the researchers in the domains of materials science and engineering materials in the recent decades (Mittal, Saini and Sinha, 2016). In general, composite materials are classified into three types based on the matrix used: polymer matrix composites, metal matrix composites, and ceramic matrix composites. Polymer matrix composites have several advantages over the other two, such as a higher specific strength-to-weight ratio, the opportunity to be formed into various sizes and shapes corrosion resistance, in addition to a simple manufacturing process, recyclability, and relatively low cost (Dahy, 2017).

Fiber-reinforced polymers have therefore effectively replaced their fairly expensive engineering plastic and heavy metal and ceramic equivalents. Typically, thermosets or thermoplastic resins serve as the matrix for fiber-reinforced plastics, which then contain either synthetic or natural fibers as reinforcement (Wang et al., 2019).

Although bacterial cellulose has a strong tension capacity, it was seen that the vulnerability increases in dried conditions. This situation also negatively affects the material when exposed to compressive forces. Therefore, in order to increase the workability, wetness of the samples were moderated through air-drying, and several composite explorations were conducted. The potential composite components were selected from the same family, cellulose. Therefore, the potentials of bacterial cellulose and plant-based cellulose composites were explored through a series of experiments and mechanical tests.

There are various types of fibers in the textile industry such as jute, cotton, bamboo, silk, and ramie and so on. While some of them are not very well received in terms of an animal friendly production process, some of them require high energy leaving high amounts of carbon footprint. In this manner, jute, cotton and bamboo were selected considering their cellulose base, environmentally friendly, animal cruelty free, and biodegradable properties.

3.3.1. Jute fibers

Jute is made from blooming plants of the *genus Corchorus*, which belongs to the *Malvaceae* family of mallows. While *Corchorus olitorius* is the main source of the fiber, *Corchorus capsularis* is said to produce superior fiber (Wang et al., 2019). The second-most organic and biodegradable fiber, jute is a great substitute when strength, thermal conductivity, and affordability are the top considerations (Islam and Alauddin, 2012).

The jute fibers are environmentally friendly and therefore jute fiber-reinforced polymer composites have recently grown in importance (Sinha, Narang and Bhattacharya, 2017). Jute fiber is typically utilized for inexpensive and basic textile items. The jute's qualities might be changed to make way for high-end, technological textiles, which would be extremely advantageous for the environment as well as cost.

The cellulose (45–71.5%), hemicelluloses (13.6–21%), and lignin (12–26%) make up jute structure (Wang et al., 2019). The lignin provides mechanical support because of the aromatic rings (ring-shaped bonds) it contains (Islam and Alauddin, 2012). Hemicellulose is another ingredient that provides strength to the cell wall (Scheller and Ulvskov, 2010). The gum is defined as any substance other than cellulose that reduces the smoothness, elasticity, and fineness of jute (Sinha, Narang and Bhattacharya, 2017).

The jute fibers have been found to have a number of mechanical properties that make them suitable for use in composite materials (Wang et al., 2019). Some of the key mechanical properties of jute fibers include:

- Tensile strength: Jute fibers have a relatively high tensile strength, which is the ability of a material to withstand a pulling force without breaking. This makes them suitable for use in composite materials that need to be strong in tension.
- Modulus of elasticity: Jute fibers also have a high modulus of elasticity, which is a measure of a material's ability to withstand a stretching force without deforming permanently. This makes them suitable for use in composite materials that need to be stiff.
- Toughness: Jute fibers have a relatively high toughness, which is the ability of a material to absorb energy and resist breaking when subjected to impact or other types of loading. This makes them suitable for use in composite materials that need to be able to withstand impact and other types of loading.
- Density: Jute fibers have a relatively low density, which makes them lightweight and suitable for use in composite materials that need to be lightweight.

The researchers have been exploring the use of jute fiber reinforced composites in various applications, taking advantage of these mechanical properties (Fagone, Loccarini and Ranocchiai, 2017; Salih et al., 2019; Chandekar, Chaudhari and Waigaonkar, 2020). Some of the key areas of exploration include:

- Building construction: Jute fiber reinforced composites have been used in the construction of load-bearing walls, columns, and beams. The jute fibers provide strength and durability to the composite material, while the other materials provide additional properties such as water resistance and fire resistance.

- Infrastructure: Jute fiber reinforced composites have also been used in infrastructure projects such as bridges, roads, and retaining walls. These composites can provide increased strength and durability while also being lightweight and easy to transport.
- Industrial: Jute fiber reinforced composites have also been used in industrial applications such as in the manufacturing of heavy equipment and machinery. The composites can provide increased strength and durability while also being resistant to corrosion and wear.
- Seismic resistance: Jute fiber reinforced composites are also being used in seismic retrofitting of buildings. The jute fibers provide the required flexure strength to the composite material and can be used to reinforce concrete and masonry structures to improve their seismic performance.

In general, jute fibers have good mechanical properties such as high tensile strength, modulus of elasticity, and toughness which make them suitable for use in composite materials. The researchers have been exploring the use of jute fiber reinforced composites in various applications, and they have shown great potential as a sustainable and eco-friendly alternative to traditional building materials.

3.3.2. Cotton fibers

The cotton fiber, also referred to as a cotton ball of fibers, is a particularly soft natural fiber. *Epidermal trichomes*, sometimes known as "hairs," found in the seeds of *Gossypium herbaceum* and some others from the same family, are the cotton's biological source. The cotton fiber in general belongs to the *Malvaceae* family, and the primary components of raw cotton are 90% cellulose, 7-8% moisture, fat, purified cotton, or absorbent cotton, which is completely cellulose and 6-7% moisture. (Kumar et al., 2022).

Depending on different chemical compositions of cotton fiber and the matrix materials, bonding between the reinforcement and matrix during the manufacturing of composites can become inconvenient (Kumar et al., 2022). Therefore, the fiber is chemically treated utilizing a variety of chemical treatment procedures in order to promote adhesion between the reinforcement and the matrix.

The cotton fibers are natural, biodegradable materials that can be used in the construction industry, particularly in the form of cotton fiber reinforced composites (Harzallah et al., 2010). Some of the key mechanical properties of cotton fibers include:

- Tensile strength: Cotton fibers have a relatively low tensile strength compared to other natural fibers such as jute and hemp, however, when combined with other materials such as polymers or cement, they can provide an adequate strength to the composite material.
- Modulus of Elasticity: Cotton fibers have a relatively low modulus of elasticity, which means that they are not very stiff on their own. However, when combined with other materials, they can provide the required stiffness to the composite material.
- Toughness: Cotton fibers have a relatively high toughness, which means that they can absorb energy and resist breaking when subjected to impact or other types of loading. This makes them suitable for use in composite materials that need to be able to withstand impact and other types of loading.
- Density: Cotton fibers have a relatively low density, which makes them lightweight and suitable for use in composite materials that need to be lightweight.

The researchers have been exploring the use of cotton fiber reinforced composites in various applications, taking advantage of these mechanical properties (Agopyan et al., 2005; Lin, Wang and Guo, 2011; Serra et al., 2019). Some of the key areas of exploration include:

- Building construction: Cotton fiber reinforced composites have been used in the construction of non-load-bearing walls, ceilings, and roofing. The cotton fibers provide insulation and fire resistance to the composite material, while the other materials provide additional properties such as water resistance.
- Industrial: Cotton fiber reinforced composites have also been used in industrial applications such as in the manufacturing of heavy equipment and machinery. The composites can provide increased toughness and resistance to impact and wear.

- Decorative applications: Cotton fibers are also used to make decorative items such as wall hangings, curtains, and upholstery.

In general, cotton fibers have good mechanical properties such as high toughness, and low density which make them suitable for use in composite materials, particularly in insulation and decorative applications, but they may not be as strong as other natural fibers like jute and hemp. Researchers have been exploring the use of cotton fiber reinforced composites in various applications, and they have shown potential as a sustainable and eco-friendly alternative to traditional building materials.

3.3.3. Bamboo fibers

One of the agricultural products that can be used in the creation of polymer composites is bamboo (Coutts, Ni and Tobias, 1994). Asia and South America are both home to a large bamboo population. Despite the fact that bamboo is regarded as a natural engineering material, most of the countries have not fully exploited its potential (Abdul Khalil et al., 2012).

Its diverse usage in the composite sector had become a result of its structural variation, mechanical characteristics, fiber extraction, chemical modification, and thermal properties (Kitagawa et al., 2005). Bamboo has a microfibrillar angle of 2-10, which is quite small, and 60% cellulose with a high amount of lignin (Abdul Khalil et al., 2012). Bamboo fiber has been used as reinforcement in a number of matrices because of its distinguished structural quality (Puglia, Biagiotti and Kenny, 2005).

Bamboo fibers are natural, biodegradable materials that can be used in the construction industry, particularly in the form of bamboo fiber reinforced composites (Mousavi et al., 2022). Some of the key mechanical properties of bamboo fibers include:

- Tensile strength: Bamboo fibers have a relatively high tensile strength, which is the ability of a material to withstand a pulling force without breaking. This makes them suitable for use in composite materials that need to be strong in tension.
- Modulus of Elasticity: Bamboo fibers also have a high modulus of elasticity, which is a measure of a material's ability to withstand a stretching force without

deforming permanently. This makes them suitable for use in composite materials that need to be stiff.

- Toughness: Bamboo fibers have a relatively high toughness, which is the ability of a material to absorb energy and resist breaking when subjected to impact or other types of loading. This makes them suitable for use in composite materials that need to be able to withstand impact and other types of loading.
- Density: Bamboo fibers have a relatively low density, which makes them lightweight and suitable for use in composite materials that need to be lightweight.

The researchers have been exploring the use of bamboo fiber reinforced composites in various applications, taking advantage of these mechanical properties (Lokesh et al., 2020; Chin et al., 2020). Some of the key areas of exploration include:

- Building construction: Bamboo fiber reinforced composites have been used in the construction of load-bearing walls, columns, and beams. The bamboo fibers provide strength and durability to the composite material, while the other materials provide additional properties such as water resistance and fire resistance.
- Infrastructure: Bamboo fiber reinforced composites have also been used in infrastructure projects such as bridges, roads, and retaining walls. These composites can provide increased strength and durability while also being lightweight and easy to transport.
- Industrial: Bamboo fiber reinforced composites have also been used in industrial applications such as in the manufacturing of heavy equipment and machinery. The composites can provide increased strength and durability while also being resistant to corrosion and wear.
- Seismic resistance: Bamboo fiber reinforced composites are also being used in seismic retrofitting of buildings. The bamboo fibers provide the required flexure strength to the composite material and can be used to reinforce concrete and masonry structures to improve their seismic performance.

In general, bamboo fibers have good mechanical properties such as high tensile strength, modulus of elasticity, and toughness which make them suitable for use in composite materials. The researchers have been exploring the use of bamboo fiber reinforced composites in various applications, and they have shown great potential as a sustainable and eco-friendly alternative to traditional building materials. Bamboo fibers are also abundant, and cost-effective making them an attractive alternative to synthetic fibers.

3.3.4. Discussion on composite potentials

As seen in the literature, natural fibers are in high demand by material scientists and designers due to their strong material properties that replace petroleum-based reinforcements. Some of them are rather further explored such as cotton, bamboo and jute in terms of the ease of production, or low processing energy, or their contribution to composite structures as reinforcements. When the tensile strength is compared, it is seen that the cotton is a relatively weaker fiber compared to bamboo and jute; whereas bamboo and jute share very similar values (Figure 12).

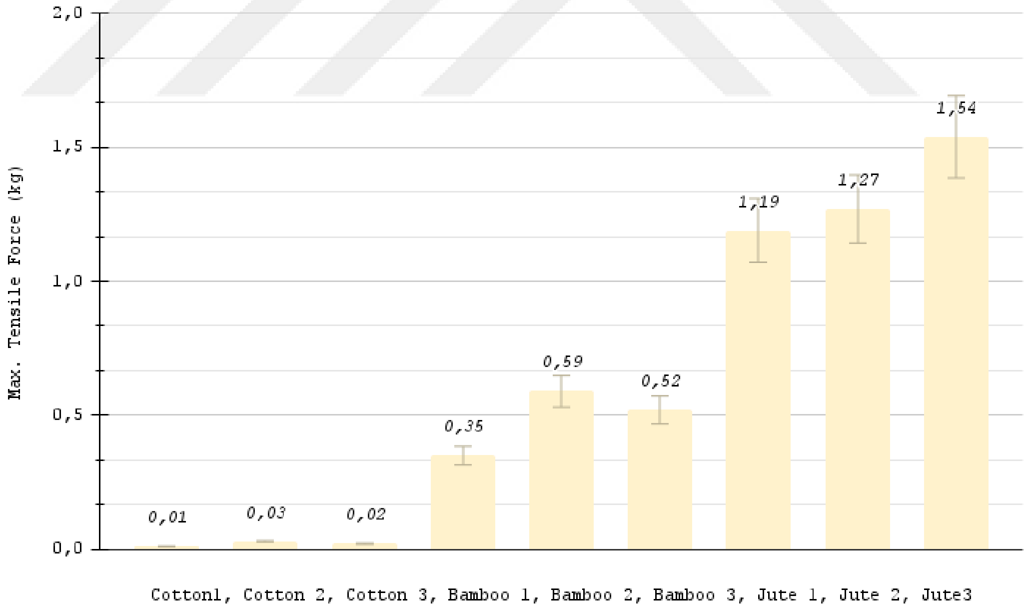

Figure 12. The maximum tensile forces that the cotton, bamboo and jute can resist, conducted in triplicate for validation

However, since these fibers are hydrophilic by their nature, the constituents besides the fibers should be removed by pretreatment in order to achieve more resilient composites. There are examples where varying NaOH concentrations are employed to physically modify the fibers in order to provide advantageous properties (Nam et al., 2011; Goriparthi, Suman and Rao, 2012; Abdul Khalil et al., 2012). A large amount of research was conducted on the tensile and flexural strength, and the improved findings were linked to the composites' increased durability from decreased water absorption due to alkali treatments (Kushawa and Kumar, 2011).

Within the context of this dissertation, in order to reduce the water absorption of the fibers, a pretreatment was conducted through NaOH solution (Figure 13). The fibers were exposed to 5% NaOH at 80°C for 90 minutes, after which they underwent three rounds of distilled water washing. Samples were dried in an oven for three hours at 70°C before the composite was made. This process is adapted from Fei et al., 2018 and Wang et al., 2019.

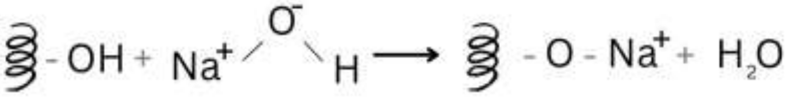

Figure 13. The chemical reaction of NaOH with cellulosic fibers (Source: Nam et al., 2011; Goriparthi, Suman and Rao, 2012)

When the BC was isolated from its original culture and reinforced with the plant fibers to obtain a workable composite, it was observed that the biocomposite became rigid as facial adhesion to plant fiber surfaces started. Besides, flexibility was protected at some level, as desired**.** After 3 days of adhesion process at room temperature, it was observed that the cellulosic composite became solid and rigid to carry dead and live loads, while at the same time flexible at a certain level. It was seen in the initial analogue bending test for BC-jute composite (Figure 14) that the structure could carry 270 times its own weight (Figure 15). Moreover, it was observed that it had a certain degree of shape-memory that enabled it to remember its original shape after it was deformed.

Figure 14. BC-jute composite sample

Figure 15. Analog bending test for BC-jute composite sample

This analog experiment opened up the potential to further investigate the properties of such composites through mechanical characterization in order to integrate the results into the computational form-finding process.

3.4. Mechanical data acquisition

After the preliminary explorations, in order to conduct a quantitative analysis to integrate mechanical and computational data, a series of mechanical experiments was conducted in a laboratory environment. In this chapter, laboratory equipment, sample properties, test conditions and results were discussed. The experiments were conducted at the Multidisciplinary Laboratory of Izmir University of Economics (IUE).

3.4.1. Laboratory equipment

The equipment used for the preliminary experiment were the incubator, autoclave and Texture Analyzer (TA-XTplus, Stable Micro Systems, UK) with the probes Mini tensile grips (A/MTG) to measure tensile characteristics. Exponent software was run for the probe. Texture analysis, which evaluates raw materials, intermediary components, and final goods, is the assessment of how food deforms and flows under the influence of stress (Materka and Strzelecki, 1998). Texture describes a food's physical characteristics that can be sensed with the fingertips, mouth, lips, or teeth. Foods come in a variety of textures, including crunchy chocolate chip cookies, deep fried potato chips, crunchy celery, hard candies, or sticky caramel etc. The quality of these foods can also be determined by texture (Salvador et al., 2009). For a variety of reasons, food texture might alter while it is being preserved. The fruits and vegetables that lose water while being stored wilt or lose their turgor pressure, making them unpalatable and leathery on the outside (Singh, Katiyar and Singh, 2014). For instance, when stored, bread can turn hard and rotten. Therefore, in order to measure such qualities, the Texture Analyzer can be used. It can conduct compression, bending, extension, cutting, extruding, and shearing tests, and while doing so, can assess a variety of qualities like fracturability, stickiness, consistency, chewability, or springiness (Tuceryan and Jain, 1993; Liu et al., 2019).

Besides the food industry, texture analyzing methods and tools are employed in material science in order to measure the characteristics of materials and composites (Stauder, Kerber and Schumacher, 2016). The rheological and fracture-mechanics methodologies were developed by material scientists to comprehend material qualities generally, whereas food scientists have been evaluating the mechanical properties to comprehend subjective texture. The materials have measurable and perceivable physical or textural/mechanical qualities. In order to make an informed process while creating a product, an engineer would typically need to be aware of and quantify the mechanical properties of a material.

A Texture Analyzer compresses or stretches a sample by moving up or down. The traveling arm is equipped with a load cell that records the force response of the specimen to deformation. The data on force, distance, and time is captured and typically displayed as a curve on a graph, which when analyzed, reveals the texture of the specimen. By allowing a wide variety of probes and fixtures to be mounted to the Texture Analyzer platform and/or arm, Texture Analyzers give users the most control and experiment flexibility for analyzing all kinds of physical qualities of solid and semi solid structures (Tang et al., 2018).

In this dissertation, considering developing a composite made out of a material that works well in tension, the Mini Tensile Grips (A/MTG) probe was attached to the Texture Analyzer in order to obtain tensile properties and the procedure was outlined in following chapters.

3.4.2. Tensile testing

In mechanics, the Force is defined as the force that is applied to the material that creates an internal force, or stress, distributed over the cross section of the material (Denzer, Barth and Steinmann, 2003). Tensile Strength (TS), also known as the Ultimate Tensile Strength (UTS), is defined as the maximum stress that a material can handle before irreversible deformation (Chica, Diez and Calzada, 2018). The flexural modulus or bending modulus is defined as the ratio of stress to strain in flexural deformation, in other words, the tendency of a material to resist bending (Smith and Hashemi, 2006). Ultimate Tensile Strength (UTS) is found by calculating the ratio of the tensile force (F) applied to the samples to the cross-sectional area (Ao). Elongation at break (ε) is calculated by the ratio of the change in the length to its original length ($\Delta L/Lo$). Young's modulus (E) is derived from the calculation of the slope of the stress-strain curve (Madhankumar et al., 2021). However, similar to the other material samples, the BC also needs to be subjected to the mechanical tests for each batch since the material properties depend on various factors such as the pH level, temperature, acidic content etc. (Hu et al., 2011).

The experiment design with the test conditions are indicated in Table 3. The composite formulation is considered as an independent variable in this experiment because it is the variable that the experimenter is manipulating or changing in order to observe the effect on the dependent variable, which is the tensile strength. The independent variable is the variable that is deliberately changed or manipulated by the experimenter in order to observe the effect on the dependent variable. In this case, different types of composite formulations (uBC: untreated BC, cBC: BC-cotton composite, bBC: BC-bamboo composite, jBC: BC-jute composite) were tested to see how they affect the tensile strength of the samples. By comparing the tensile strength of the samples made with different material formulations, which formulation results in the highest tensile strength can be determined.

Table 3. Experiment design with the test conditions

Variable	**Description**	**T (°C)**	**M_x (%)**	**W (mm)**	**T (mm)**	**L (mm)**	**Fiber gap size (mm)**	**Loading rate**
Indepen-dent variable	Composite formulation	-	-	-	-	-	1	-
Depen-dent variable	Tensile strength	-	-	-	-	-	-	-
Control group	uBC: untreated BC	22.0 ± 2.0	53.2	30	1	80	-	0.5 mm/s in tension mode
Experi-mental groups	cBC bBC jBC	22.0 ± 2.0	26,7-42,8 25,7-70,6 21,4-39,5	30	1	80	0 3 5 6 1	0.5 mm/s in tension mode

The tensile strength is considered the dependent variable in this experiment since it is the variable being measured or observed to see how it changes in response to changes in the independent variable, which is the type of material formulation. The dependent variable is the variable that is being measured or observed in order to determine how it is affected by changes in the independent variable. In this case, the tensile strength of samples made with different types of material formulations (uBC: untreated BC, cBC: BC-cotton composite, bBC: BC-bamboo composite, jBC: BC-jute composite) were tested to see how the material formulation affects the tensile strength. By comparing the tensile strength of the samples made with different material formulations, which formulation results in the highest tensile strength can be determined.

uBC (untreated BC) is considered the control group in this experiment because it serves as a baseline or reference point against which the experimental groups (cBC: BC-cotton composite, bBC: BC-bamboo composite, jBC: BC-jute composite) can be compared. The control group is a group in an experiment that is not exposed to the experimental material formulation, it serves as a reference point to compare the results of the experimental groups. In this case, the experimenter is testing the tensile strength of samples made with different types of material formulations. By using uBC as the control group, the experimenter can compare the tensile strength of the untreated BC samples to the tensile strength of the samples made with the other material formulations (cBC, bBC, jBC). This will allow the experimenter to see how the addition of cotton, bamboo, or jute fibers affects the tensile strength of the samples. It is important to have a control group in an experiment to have a reference point to compare the results of the experimental groups and to control for any extraneous variables that may influence the results. By using uBC as the control group, the experimenter can conclude that any differences in tensile strength between the control group and the experimental groups are due to the material formulation, and not due to any other factors.

The tests were performed at room temperature, T = 22.0 ± 2.0 °C. The samples were prepared and mounted between an upper and a lower clamp, and force was applied from the upper clamp with a speed of 0.5 mm/s in tension mode (positive force). The settings of the T.A. including the load cell capacity (g), motor steps/mm, low/high point resistance, force filter and test time are defined. The experiments were repeated with three identical samples of five different composites for validation.

The mechanical experiments were conducted with TA-XTplus with the probe: A/MTG for tensile tests. A/MTG provides the following values: Force (kg), distance (mm), time (sec), strength (kg/mm^2) and strain (%). Other values such as Stress (σ), Young's modulus (E) and elongation at break (A) could be derived. The composites were tested according to a standard sampling method ASTM D882-18 for quantitative analysis. According to the ASTM D882-18 specifications, non-fibrous natural constituents of the samples must be removed (Davis, 2004). Detailed instructions can be found in the guide (ASTM International, 2018). It covers the procedures for the thin sheets under 1 mm thickness. Therefore, BC and its composites with different fiber types, provided that the thicknesses are not more than 1 mm, can be tested. A/MTG was conducted for four types of samples with different fiber gaps: Untreated BC biofilm (uBC), BC-cotton composite (cBC), BC-bamboo composite (bBC) and BC-jute composite (jBC) (Figure 16).

Figure 16. Untreated BC biofilm (uBC), BC-jute (jBC), BC-cotton (cBC), BC-bamboo (bBC)

The composites were grown together with the BC, within the same container and under the same conditions for 34 days. 8 days after the cultivation, each sample was reduced down into three identical pieces (80mm x 30mm x 1mm) with varying sizes of fiber gaps (Figure 17), allowing testing the samples in triplicate in order to validate the results. Each material sample was weighted with a microbalance during the tests (Table 4) and in dry condition (Table 5) in order to measure the amount of moisture during the tests (Table 6). The experiments were conducted three times for each sample for validation. The testing process is illustrated in Figure 18.

Figure 17. An example of the composite samples, demonstrating the fiber gap differences

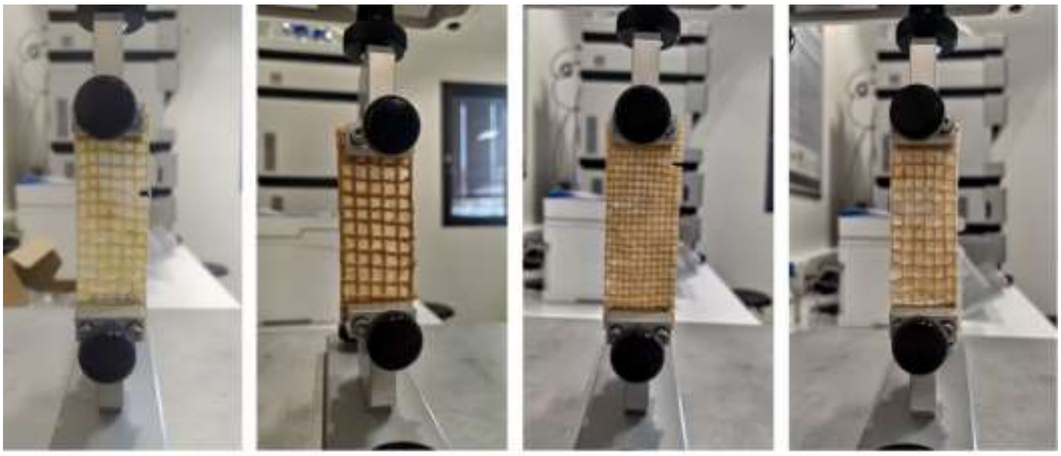

Figure 18. An example of tensile testing process for composite samples

Table 4. Sample weights (gr) during the tests

	cBC1 (1cm)	cBC2 (0.6cm)	cBC3 (0.5cm)	cBC4 (0.3cm)	cBC5 (0cm)
1	2,1014	2,2218	2,4812	3,3684	3,4411
2	2,1021	2,2219	2,4826	3,3628	3,4401
3	2,1009	2,2220	2,4821	3,3621	3,4419
	bBC1 (1cm)	**bBC2 (0.6cm)**	**bBC3 (0.5cm)**	**bBC4 (0.3cm)**	**bBC5 (0cm)**
1	1,8151	1,6841	2,0068	2,2728	3,4801
2	1,8174	1,6844	2,0076	2,2746	3,4812
3	1,8101	1,6856	1,9965	2,2773	3,4824
	jBC1 (1cm)	**jBC2 (0.6cm)**	**jBC3 (0.5cm)**	**jBC4 (0.3cm)**	**jBC5 (0cm)**
1	2,2819	2,4219	2,5197	3,1301	3,3145
2	2,2816	2,4221	2,5084	3,1346	3,3121
3	2,2825	2,4262	2,5123	3,1321	3,3098

Table 5. Weights (gr) for dried samples

	cBC1 (1cm)	**cBC2 (0.6cm)**	**cBC3 (0.5cm)**	**cBC4 (0.3cm)**	**cBC5 (0cm)**
1	1,2012	1,3217	1,5211	2,4682	2,5010
2	1,2051	1,3276	1,5222	2,4622	2,4991
3	1,2096	1,3290	1,5296	2,4626	2,5023
	bBC1 (1cm)	**bBC2 (0.6cm)**	**bBC3 (0.5cm)**	**bBC4 (0.3cm)**	**bBC5 (0cm)**
1	0,9165	0,7842	1,1066	1,3722	2,5801
2	0,9099	0,7899	1,1078	1,3747	2,5877
3	0,9146	0,7898	1,1067	1,3786	2,5832
	jBC1 (1cm)	**jBC2 (0.6cm)**	**jBC3 (0.5cm)**	**jBC4 (0.3cm)**	**jBC5 (0cm)**
1	1,3816	1,5035	1,5602	2,1784	2,6001
2	1,3801	1,5075	1,5655	2,1783	2,6027
3	1,3804	1,4997	1,5672	2,1893	2,5932

Table 6. Moisture levels (%) during tests [MC= (w-d) / w * 100]

	cBC1 (1cm)	**cBC2 (0.6cm)**	**cBC3 (0.5cm)**	**cBC4 (0.3cm)**	**cBC5 (0cm)**
1	42,8	40,5	38,7	26,7	27,3
2	42,7	40,2	38,7	26,8	27,4
3	42,4	40,2	38,4	26,8	27,3
	bBC1 (1cm)	**bBC2 (0.6cm)**	**bBC3 (0.5cm)**	**bBC4 (0.3cm)**	**bBC5 (0cm)**
1	49,5	53,4	44,9	39,6	25,9
2	49,9	53,1	44,8	39,6	25,7
3	49,5	70,6	44,6	39,5	25,8
	jBC1 (1cm)	**jBC2 (0.6cm)**	**jBC3 (0.5cm)**	**jBC4 (0.3cm)**	**jBC5 (0cm)**
1	39,5	37,9	38,1	30,4	21,6
2	39,5	37,8	37,6	30,5	21,4
3	39,5	38,2	37,6	30,1	21,7

3.4.3. Tensile test results

The results of tensile tests corresponded to the values found in the literature for uBC. However, since there is no systematic framework or database for cBC, bBC or jBC, the results could not be compared with other studies in the literature. The comparison showed that the best performing composite in terms of tension was found to be cBC5, bBC4 and jBC4 with lesser material and higher tensile strength values (Table 7).

Table 7. The ratio of maximum tensile strength to sample weights

cBC				
Sample ID	**Max Tensile Strength**	**Test weight**	**Ratio**	**Rank**
cBC1	1622	2,10	772,38	5
cBC2	3749	2,22	1688,7	2
cBC3	3831	2,48	1544,7	3
cBC4	4876	3,36	1451,1	4
cBC5	7850	3,44	2281,9	**1**
bBC				
Sample ID	**Max Tensile Strength**	**Test weight**	**Ratio**	**Rank**
bBC1	4292	1,81	2371,2	4
bBC2	9857	1,68	5867,2	2
bBC3	11174	2	5587	5
bBC4	16595	2,27	7310,5	**1**
bBC5	16642	3,48	4782,1	3
jBC				
Sample ID	**Max Tensile Strength**	**Test weight**	**Ratio**	**Rank**
jBC1	5216	2,28	2287,7	5
jBC2	8210	2,42	3392,5	3
jBC3	8351	2,51	3327	4
jBC4	16632	3,13	5313,7	**1**
jBC5	16650	3,31	5030,2	2

It was also seen that the uBCs have very close tensile strength values with cBC1. The cBC2-5 and other composites bBC1-5 and jBC1-5 showed higher tensile strength values which indicates that the cotton density needs to be higher within the composites or other alternatives bamboo and jute can be used where higher tensile strength values are required.

Consequently, the results showed that it is promising and feasible to use BC-based composites in potential structural applications. The tensile test results differed both in terms of the type of the fibers and the size of the fiber gaps. It was seen that the highest tensile strength was achieved with the samples with 0.0 cm fiber gaps, while the lowest values were obtained with the 1 cm gaps.

It was already hypothetically expected that wider the gap lesser the tensile strength and vice versa. However, this causes material waste while the optimum results could be achieved by using lesser plant cellulose fibers. Therefore, the ratio of the maximum tensile strength values to weights were compared in order to declare the optimum composite for potential applications. The optimum composite for cBC is cBC5, while bBC’s is bBC4 and jBC's is jBC4. Another constant affecting the tensile test results was the clamping condition. If the clamps are too tight, then it causes a deformation at the very bottom, and if the clamping is too loose, then the results become misleading as well. This affects the tensile test values as seen in Figure 19. In order to avoid these undesirable situations, the clamping was carefully conducted. An example of texture analysis report is indicated in Table 8.

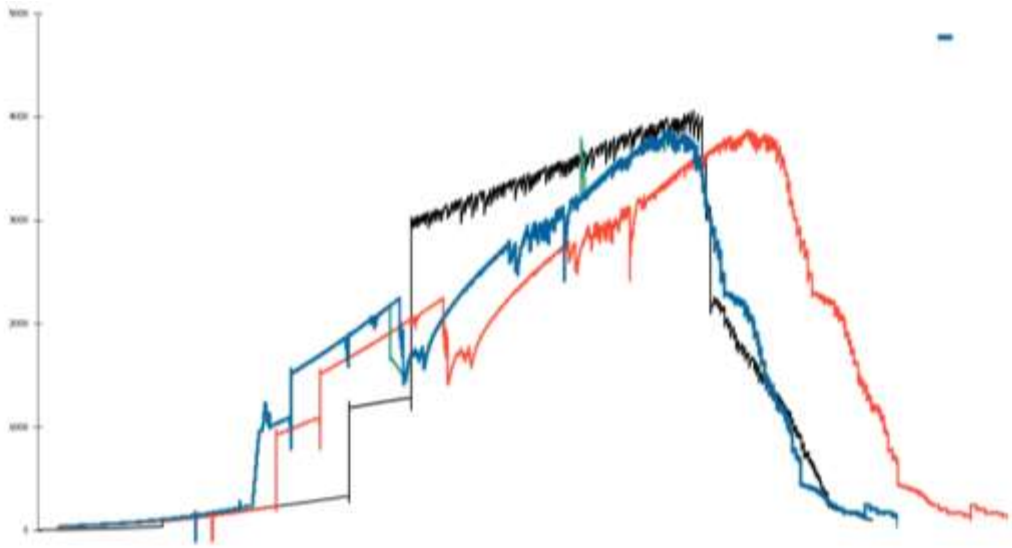

Figure 19. A misleading tensile test result due to the sliding clamp conditions

Table 8. An example of a texture analysis report, conducted for cBC3

Sequence Title:	**Test Mode:**	**Pre-Test Speed:**	**Test Speed:**	**Post-Test Speed:**	**Target Mode:**	**Force:**
1 Return to Start	Tension	8,30 mm/sec	0,5 mm/sec	10,00 mm/sec	Distance	100,0 g
Distance:	**Strain:**	**Trigger Type:**	**Trigger Force:**	**Probe:**	**Batch:**	**Points per sec**
200,000 mm	77,6 %	Button	5,0 g	A/MTG ; Miniature Tensile Grips	cBC3	500

The detailed tensile test results for the uBC, cBC, bBC and jBC specimen in triplicate are given below:

uBC results

In the literature, TS values for untreated BC films have been reported between 5-96 MPa (Cai and Kim, 2010). There seems to be a wide range of TS values since the cellulose properties depend on the assembling order that is controlled by the culture medium, the conditions of fermentation and treatment, as well as the conditions of measurement or the moisture amount (Hu et al., 2011). The uBC tensile test results showed (Figure 20-21) that the maximum strain $[L-L_o/(L_o t)]$ has been found to be ±26,47%, and the Ultimate Tensile Strength (UTS) was found to be ±13,5 MPa (F/A_0) for the untreated BC biofilm, uBC, as seen in Table 9.

Table 9. uBC results in triplicate

SAMPLE ID	**DIMENSIONS** *(mm)*	**MAX FORCE** *(g)*	**MAX STRENGTH** *(MPa)*	**MAX STRAIN** *(%)*
uBC1	30x80x1	4050,9982	13,5	26,47
uBC2	30x80x1	4050,9985	13,5	26,47
uBC3	30x80x1	4050,9985	13,5	26,47

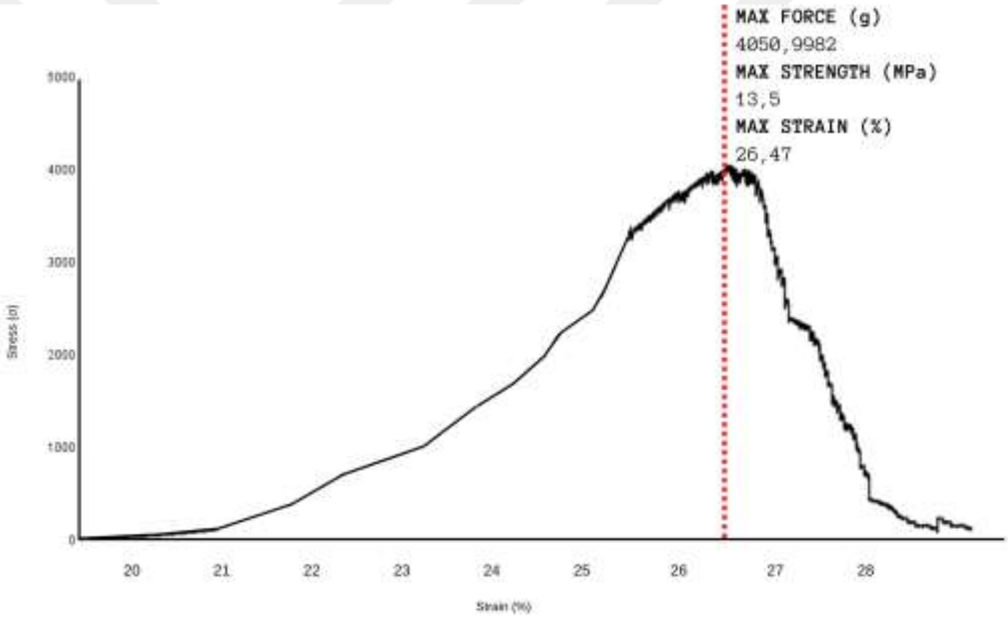

Figure 20. Stress-strain graph for uBC1.1 (max.)

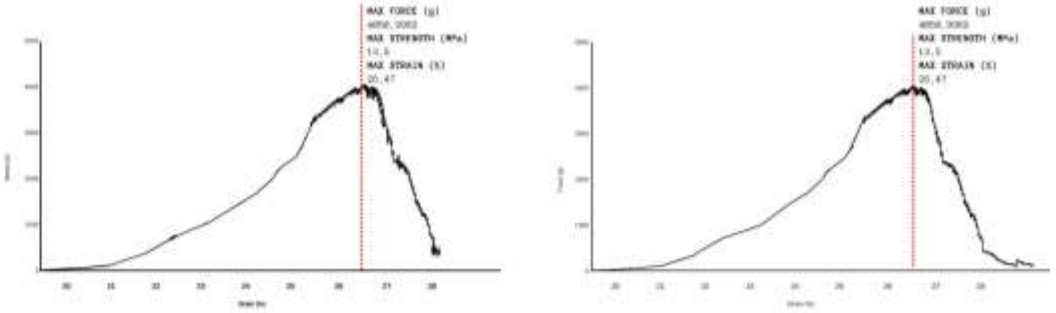

Figure 21. Stress-strain graphs for uBC1.2 and uBC1.3

cBC results

The cBC tensile tests were conducted for the composites with five different fiber gaps (1 cm, 0.6 cm, 0.5 cm, 0.3 cm, 0 cm) in triplicate as seen in Table 10. The cBC tensile test results showed that the Ultimate Tensile Strength (UTS), which indicates the maximum strength that the specimen demonstrate against tensile force, was found to be ±16,22 MPa (F/A_0) for cBC1; ±3749 MPa for cBC2; ±3830,66 MPa for cBC3; ±4876,00 MPa for cBC4; and ±7849,66 MPa for cBC5. The maximum strain [$L-L_o/(L_ot)$] has been found to be ±35,2% for cBC1; ±76,9 for cBC2; ±77,6 for cBC3; ±82,4 for cBC4; and ±96,2 for cBC5. Since no other studies were reported for such composites, the results (Table 11) could not be compared with the findings in the literature. The stress/strain graphs were given in Figure 22-31.

Table 10. Properties of cBC samples

Sample ID	Dimensions (mm)	Composite type	Fiber gaps (cm)
cBC1	80 x 30 x 1	BC-cotton	1
cBC2	80 x 30 x 1	BC-cotton	0.6
cBC3	80 x 30 x 1	BC-cotton	0.5
cBC4	80 x 30 x 1	BC-cotton	0.3
cBC5	80 x 30 x 1	BC-cotton	0

Table 11. cBC tensile testing results

SAMPLE ID	COMPO-SITE TYPE	FIBER GAPS *(cm)*	DIMENSIONS *(mm)*	MAX FORCE *(g)*	MAX STRENGTH *(MPa)*	MAX STRAIN *(%)*
cBC1	BC-cotton	1	80x30x1	4868	16,22	35,2
cBC2	BC-cotton	0.6	80x30x1	11247	3749	76,9
cBC3	BC-cotton	0.5	80x30x1	11492	3830,66	77,6
cBC4	BC-cotton	0.3	80x30x1	14628	4876	82,4
cBC5	BC-cotton	0	80x30x1	23549	7849,66	96,2

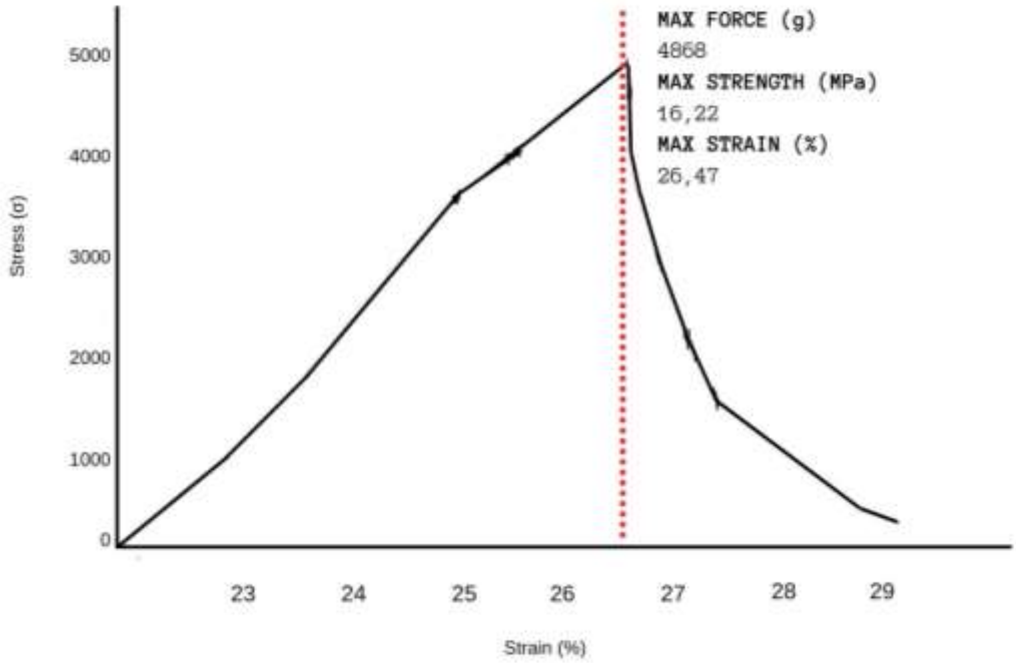

Figure 22. Stress-strain graph for cBC1.1 (max.)

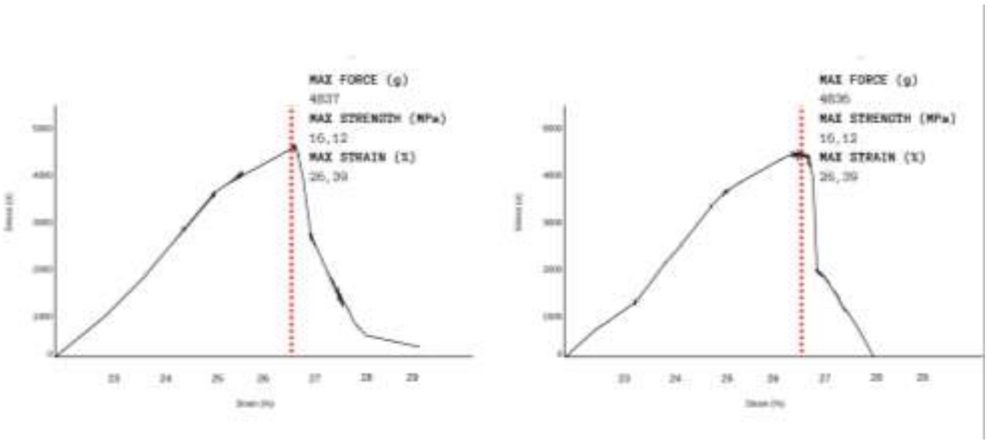

Figure 23. Stress-strain graphs for cBC1.2 and cBC1.3

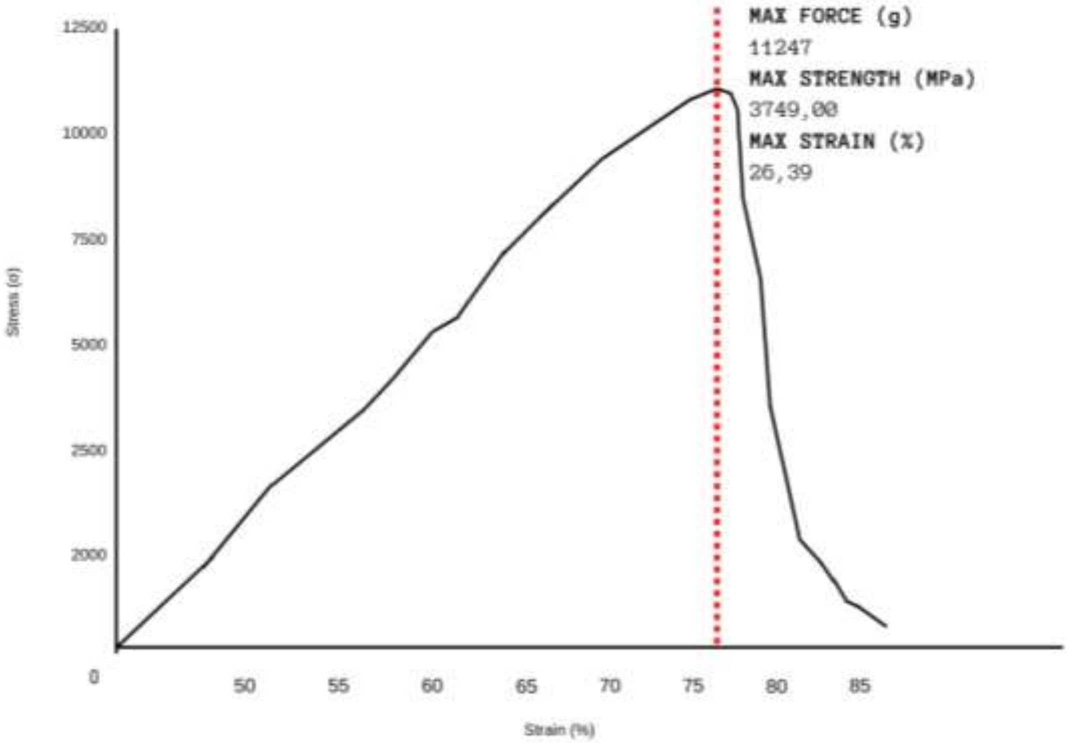

Figure 24. Stress-strain graph for cBC2.1 (max.)

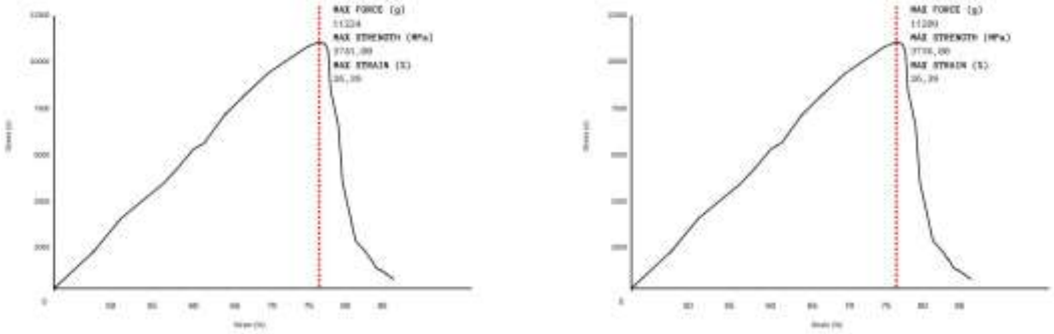

Figure 25. Stress-strain graphs for cBC2.2 and cBC2.3

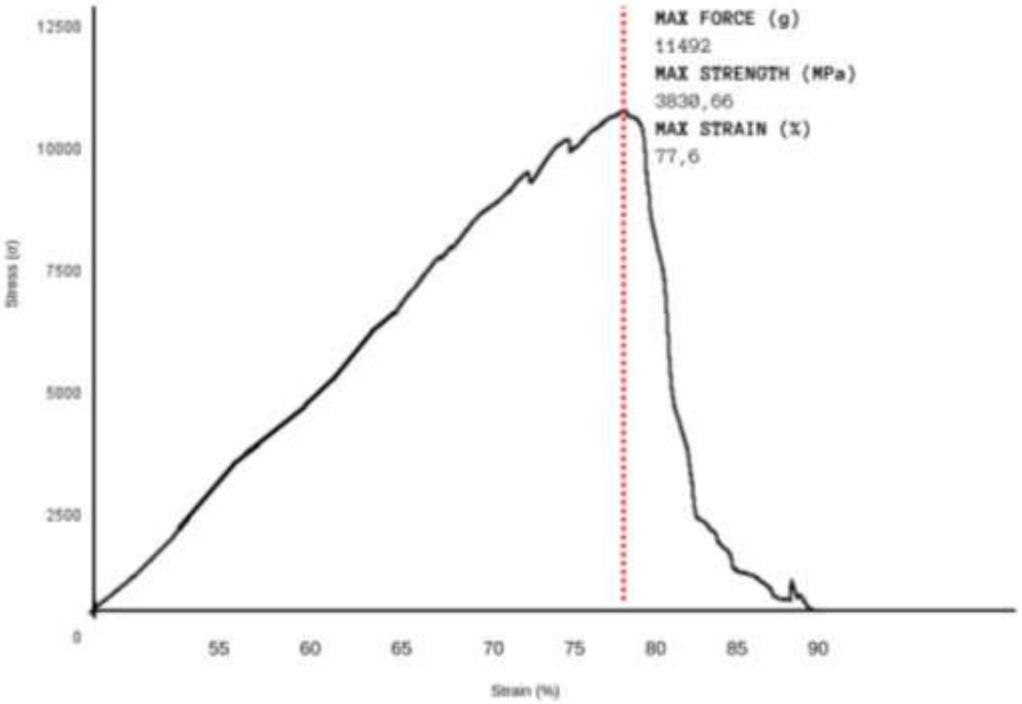

Figure 26. Stress-strain graph for cBC3.1 (max.)

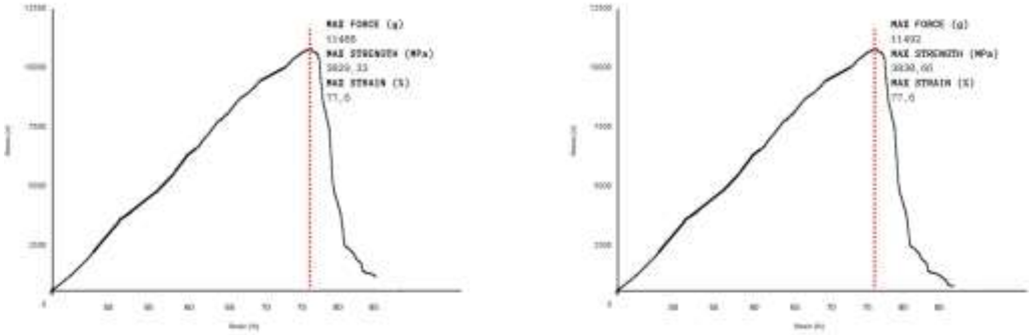

Figure 27. Stress-strain graphs for cBC3.2 and cBC3.3

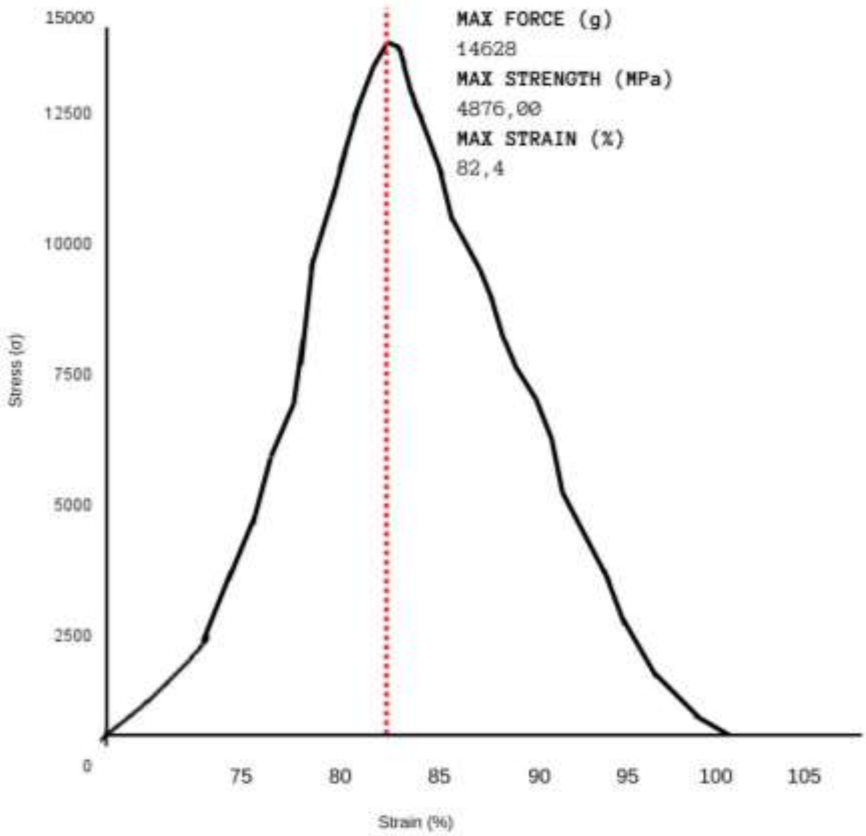

Figure 28. Stress-strain graph for cBC4.1 (max.)

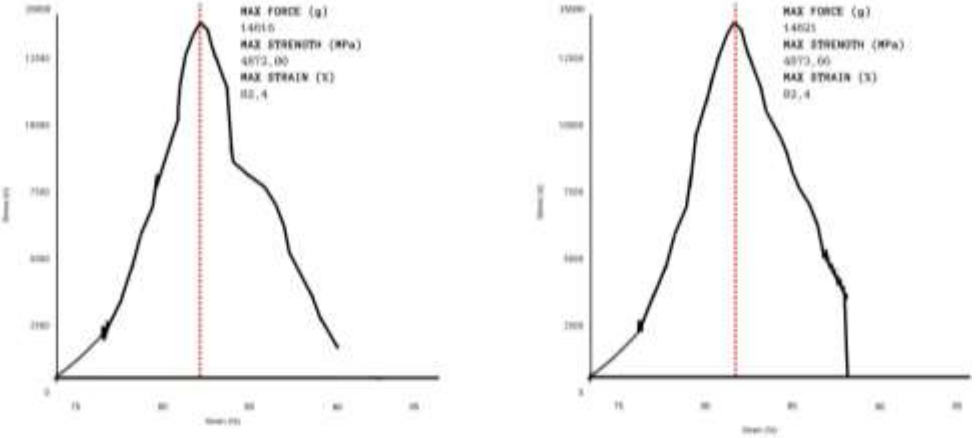

Figure 29. Stress-strain graphs for cBC4.2 and cBC4.3

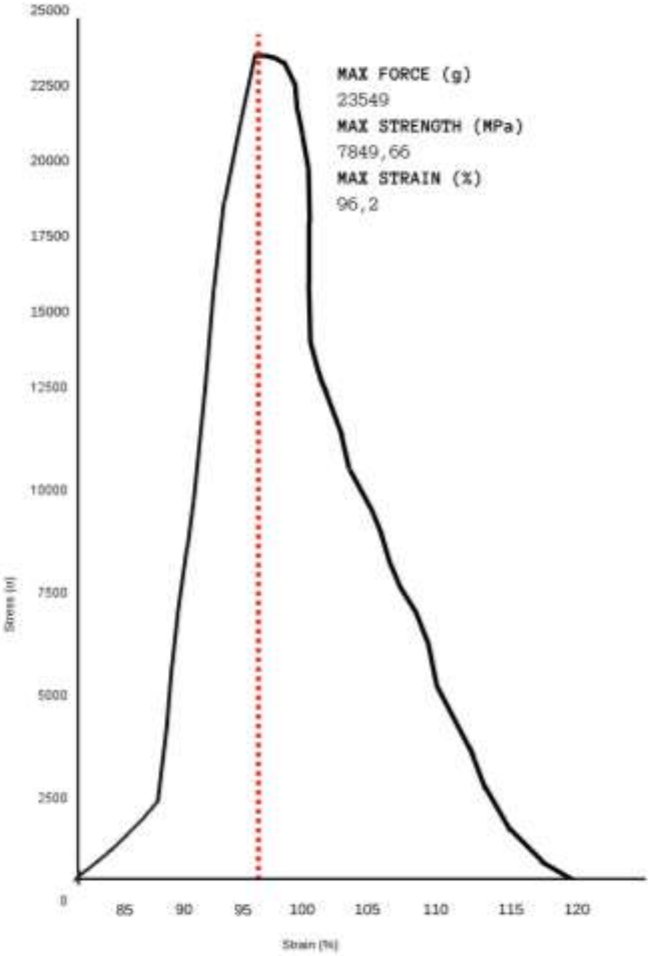

Figure 30. Stress-strain graph for cBC5.1 (max.)

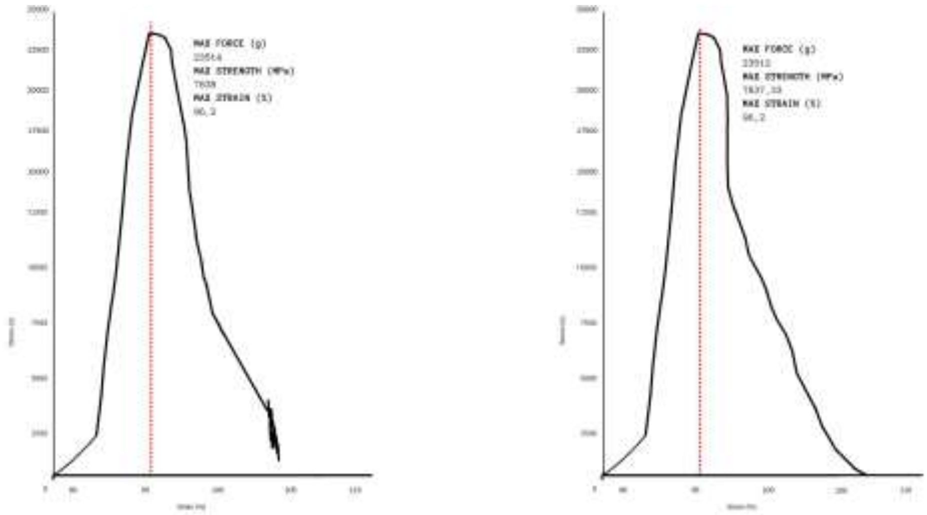

Figure 31. Stress-strain graphs for cBC5.2 and cBC5.3

bBC results

The bBC tensile tests were conducted for the composites with five different fiber gaps (1 cm, 0.6 cm, 0.5 cm, 0.3 cm, 0 cm) in triplicate as seen in Table 12 and Figure 32-41. The bBC tensile test results showed that the Ultimate Tensile Strength (UTS), which indicates the maximum strength that the specimen demonstrate against tensile force, was found to be ±16,22 MPa (F/A_0) for bBC1; ±3749 MPa for bBC2; ±3830,66 MPa for bBC3; ±4876,00 MPa for bBC4; and ±7849,66 MPa for bBC5. The maximum strain $[L-L_o/(L_o t)]$ has been found to be ±35,2% for bBC1; ±76,9 for bBC2; ±77,6 for bBC3; ±82,4 for bBC4; and ±96,2 for bBC5. Since no other studies were reported for such composites, the tensile test results for bBC composites (Table 13) could not be compared with the findings in the literature.

Table 12. Properties of bBC samples

Sample ID	**Dimensions (mm)**	**Composite type**	**Fiber gaps (cm)**
bBC1	80 x 30 x 1	BC-bamboo	1
bBC2	80 x 30 x 1	BC-bamboo	0.6
bBC3	80 x 30 x 1	BC-bamboo	0.5
bBC4	80 x 30 x 1	BC-bamboo	0.3
bBC5	80 x 30 x 1	BC-bamboo	0

Table 13. bBC tensile testing results

SAMPLE ID	**COMPOSITE TYPE**	**FIBER GAPS** *(cm)*	**DIMENSIONS** *(mm)*	**MAX FORCE** *(g)*	**MAX STRENGTH** *(MPa)*	**MAX STRAIN** *(%)*
bBC1	BC-bamboo	1	80x30x1	12876	4292	62,4
bBC2	BC-bamboo	0.6	80x30x1	29573	9857	89,7
bBC3	BC-bamboo	0.5	80x30x1	33523	11174	97,8
bBC4	BC-bamboo	0.3	80x30x1	49786	16595	98,2
bBC5	BC-bamboo	0	80x30x1	49928	16642	99,1

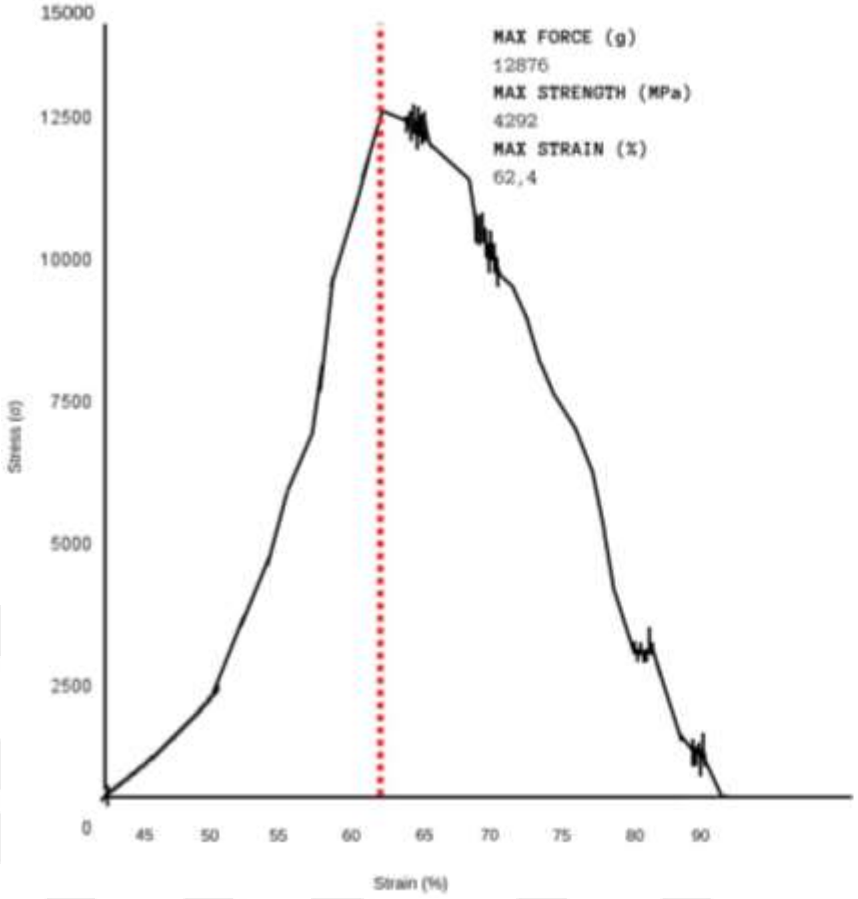

Figure 32. Stress-strain graph for bBC1.1 (max.)

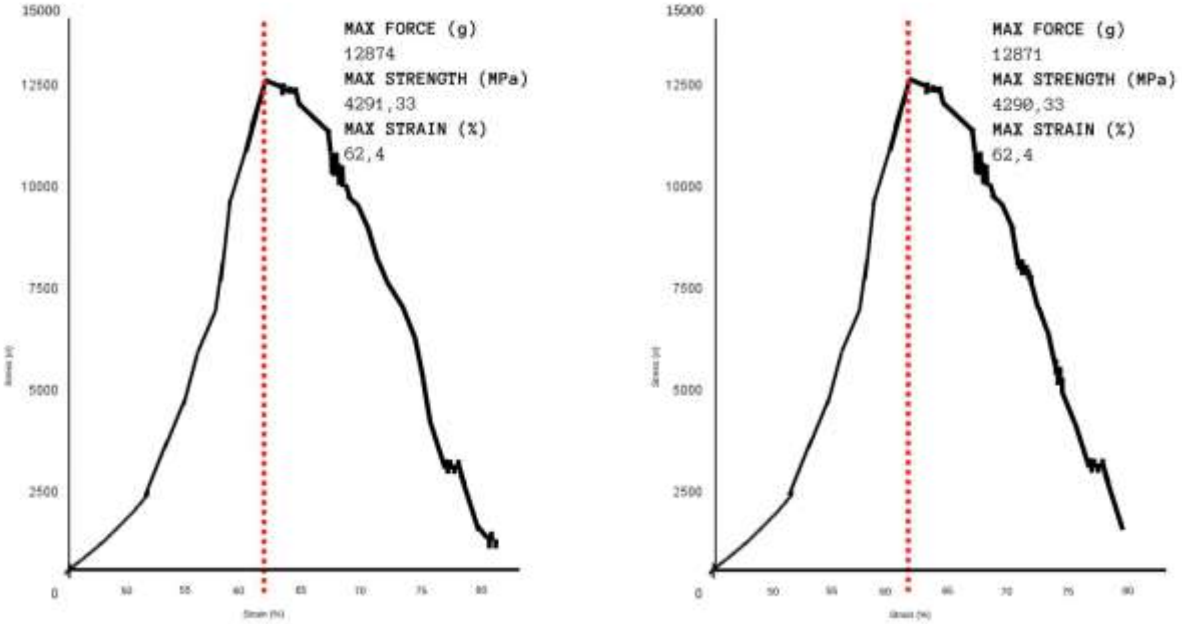

Figure 33. Stress-strain graphs for bBC1.2 and bBC1.3

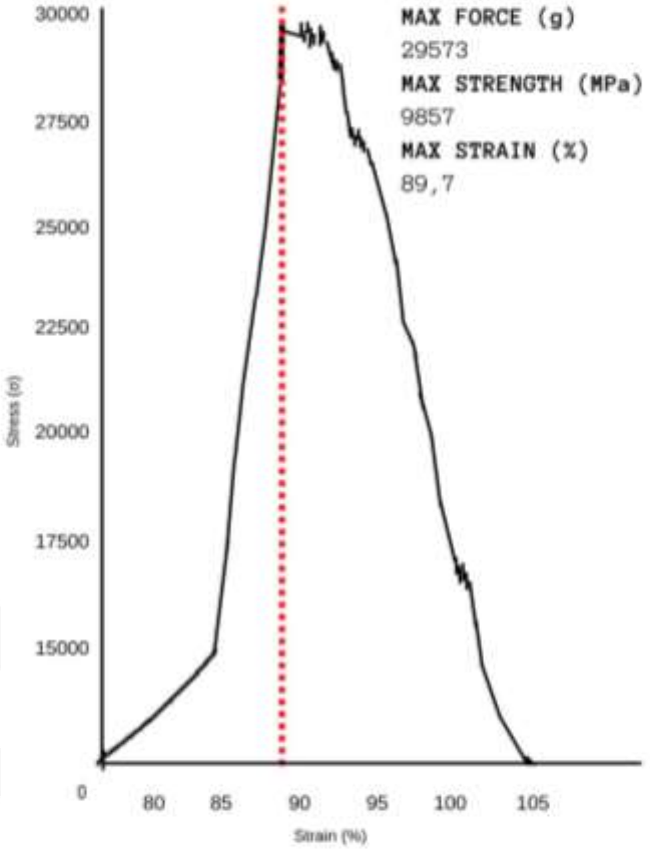

Figure 34. Stress-strain graph for bBC2.1 (max.)

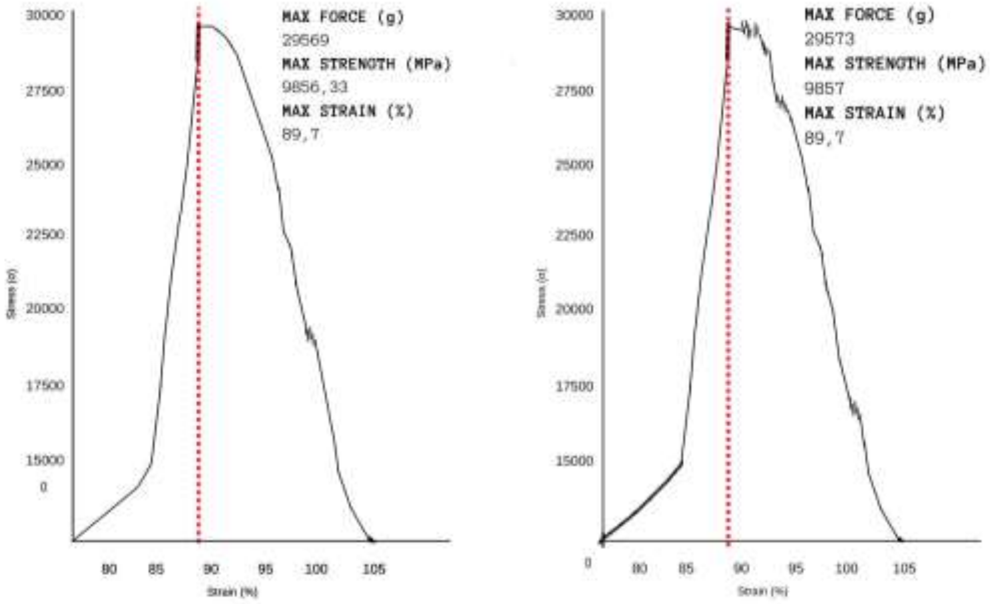

Figure 35. Stress-strain graphs for bBC2.2 and bBC2.3

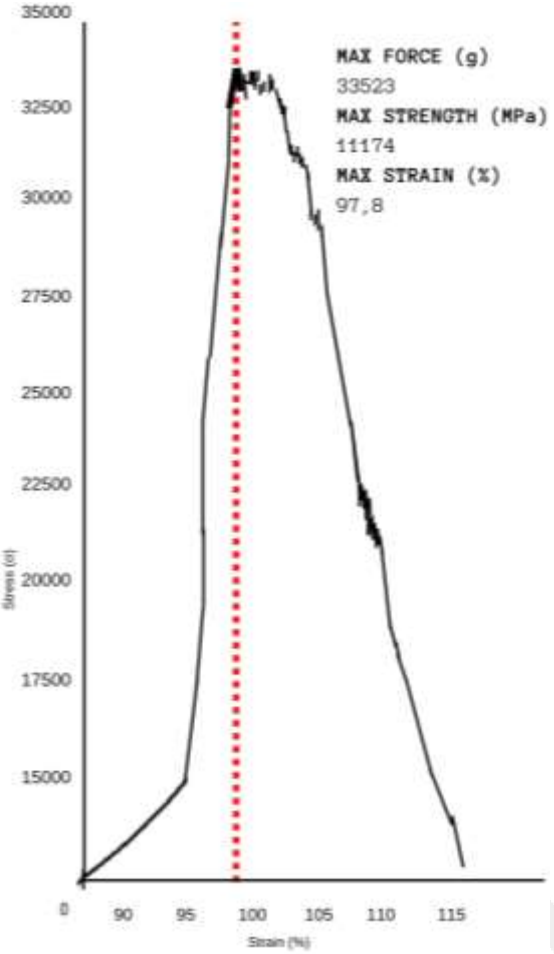

Figure 36. Stress-strain graph for bBC3.1 (max.)

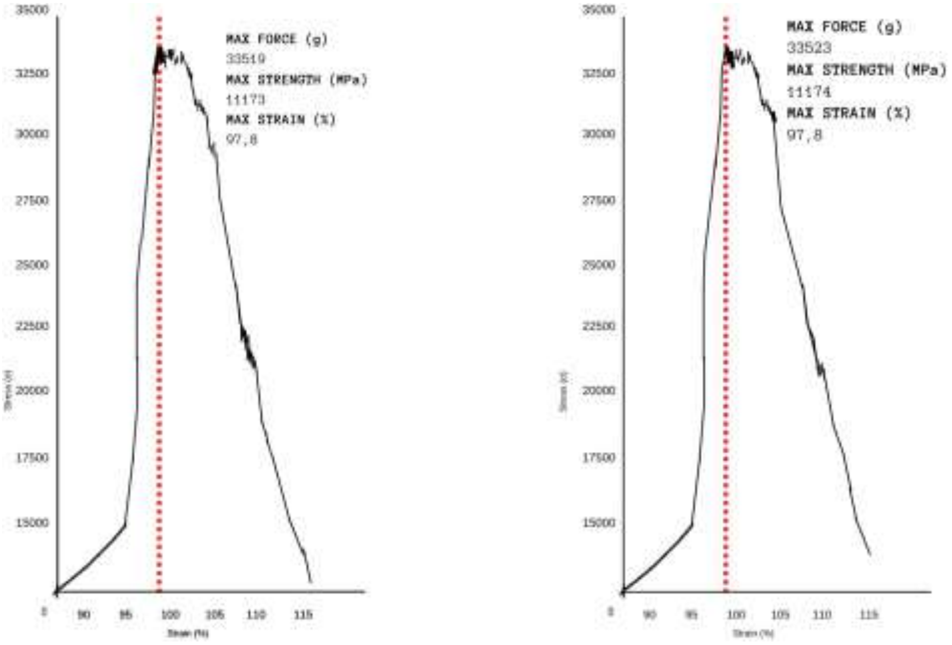

Figure 37. Stress-strain graphs for bBC3.2 and bBC3.3

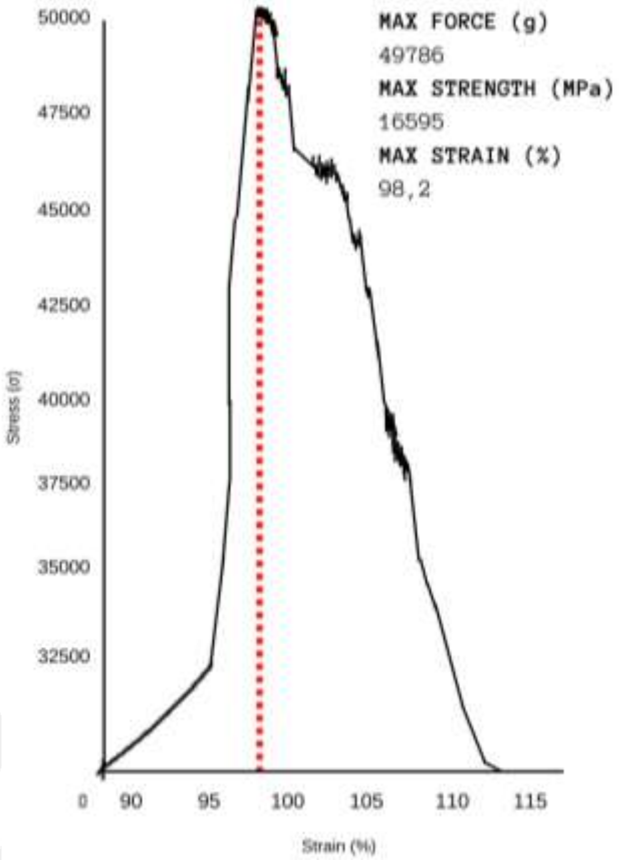

Figure 38. Stress-strain graph for bBC4.1 (max.)

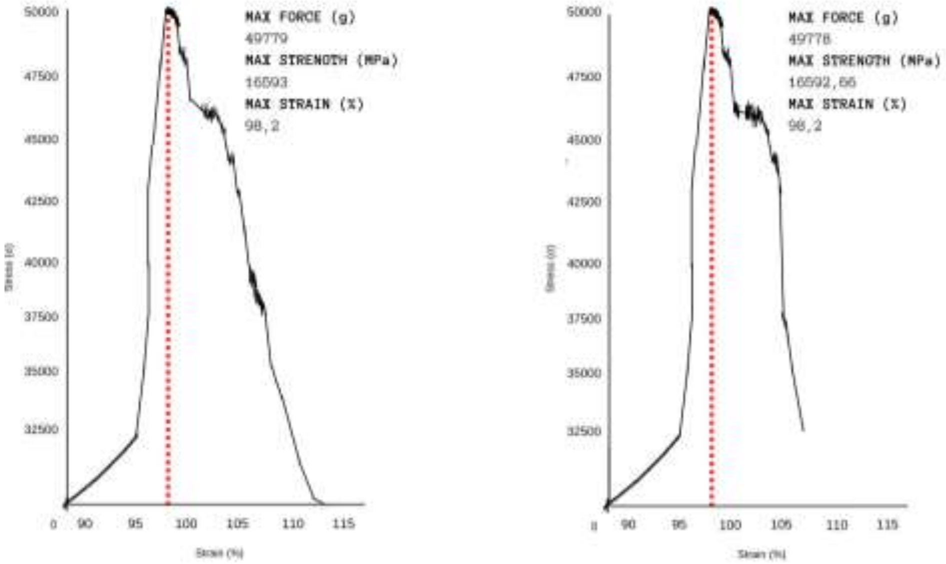

Figure 39. Stress-strain graphs for bBC4.2 and bBC4.3

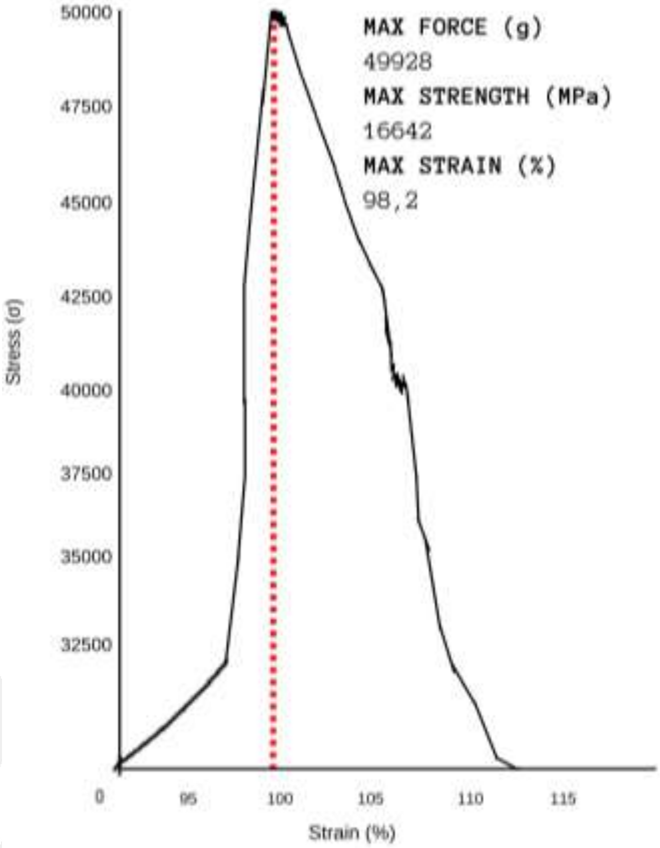

Figure 40. Stress-strain graph for bBC5.1 (max.)

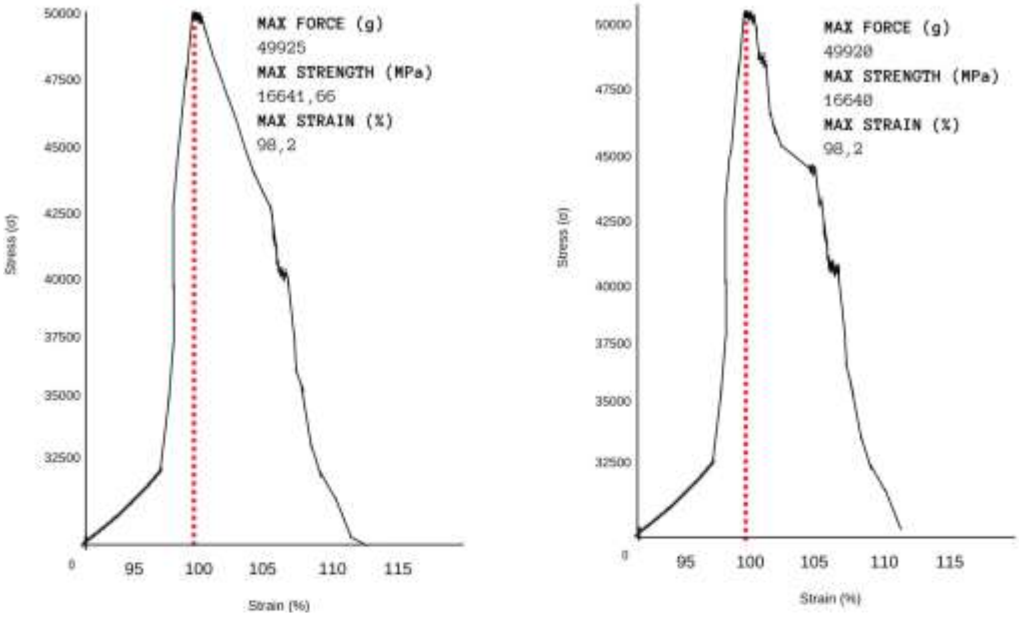

Figure 41. Stress-strain graphs for bBC5.2 and bBC5.3

jBC results

The jBC tensile tests were conducted for the composites with five different fiber gaps (1 cm, 0.6 cm, 0.5 cm, 0.3 cm, 0 cm) in triplicate as seen in Table 14 and Figure 42-51. The jBC tensile test results showed that the Ultimate Tensile Strength (UTS), which indicates the maximum strength that the specimen demonstrate against tensile force, was found to be ±5216 MPa (F/A_0) for jBC1; ±8210 MPa for jBC2; ±8351 MPa for jBC3; ±19841 MPa for jBC4; and ±30595 MPa for jBC5. The maximum strain [$L-L_o/(L_o t)$] has been found to be ±42,4% for jBC1; ±64,8 for jBC2; ±79,7 for jBC3; ±82,4 for jBC4; and ±84,1 for jBC5. Since no other studies were reported for such composites, the tensile test results for jBC composites (Table 15) could not be compared with the findings in the literature.

Table 14. Properties of jBC samples

Sample ID	**Dimensions (mm)**	**Composite type**	**Fiber gaps (cm)**
jBC1	80 x 30 x 1	BC-jute	1
jBC2	80 x 30 x 1	BC-jute	0.6
jBC3	80 x 30 x 1	BC-jute	0.5
jBC4	80 x 30 x 1	BC-jute	0.3
jBC5	80 x 30 x 1	BC-jute	0

Table 15. jBC tensile testing results

SAMPLE ID	**COMPO-SITE TYPE**	**FIBER GAPS** *(cm)*	**DIMENSIONS** *(mm)*	**MAX FORCE** *(g)*	**MAX STRENGTH** *(MPa)*	**MAX STRAIN** *(%)*
jBC1	BC-jute	1	80x30x1	15649	5216	42,4
jBC2	BC-jute	0.6	80x30x1	24631	8210	64,8
jBC3	BC-jute	0.5	80x30x1	25052	8351	79,7
jBC4	BC-jute	0.3	80x30x1	49896	16632	82,4
jBC5	BC-jute	0	80x30x1	49952	16650	84,1

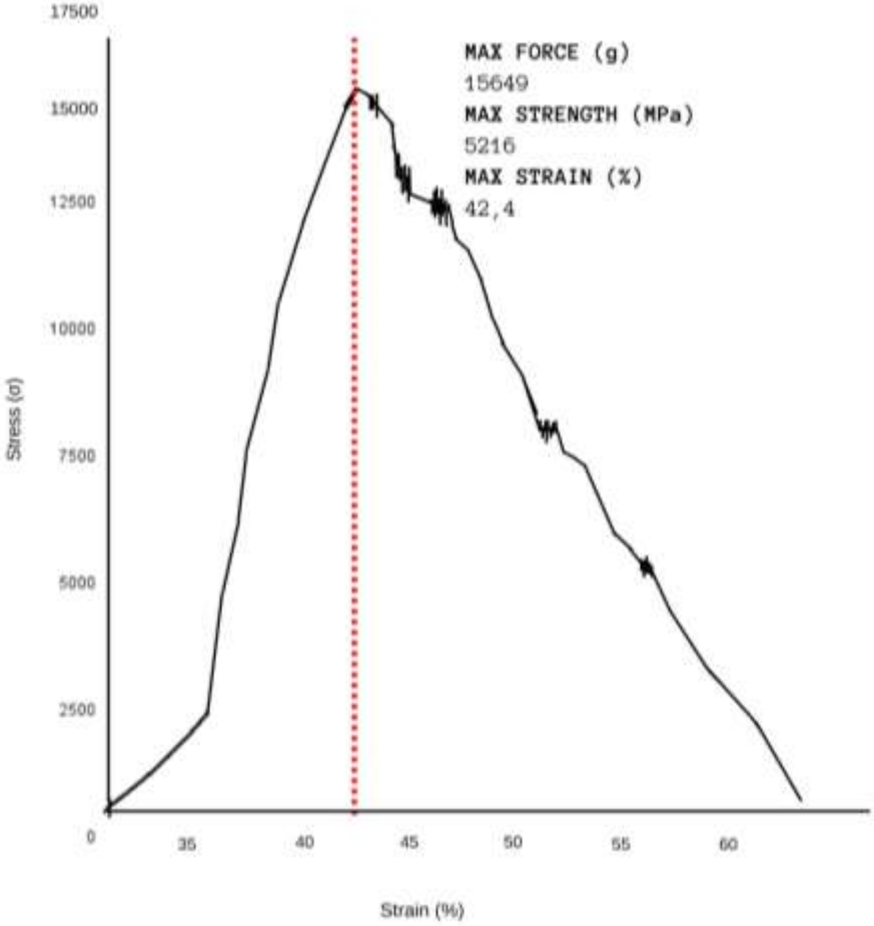

Figure 43. Stress-strain graph for jBC1.1 (max.)

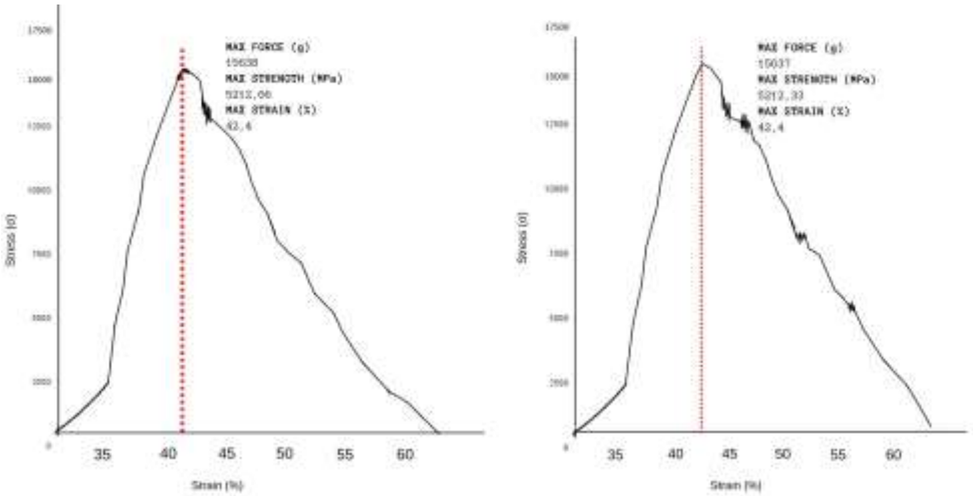

Figure 44. Stress-strain graphs for jBC1.2 and jBC1.3

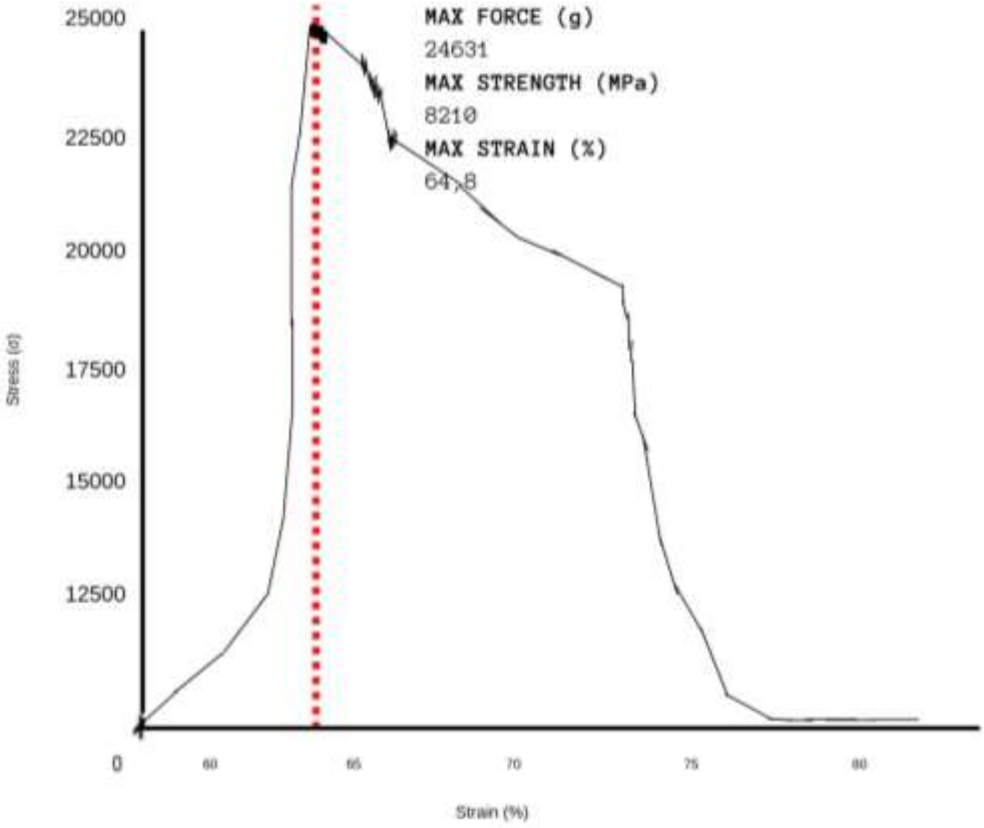

Figure 45. Stress-strain graph for jBC2.1 (max.)

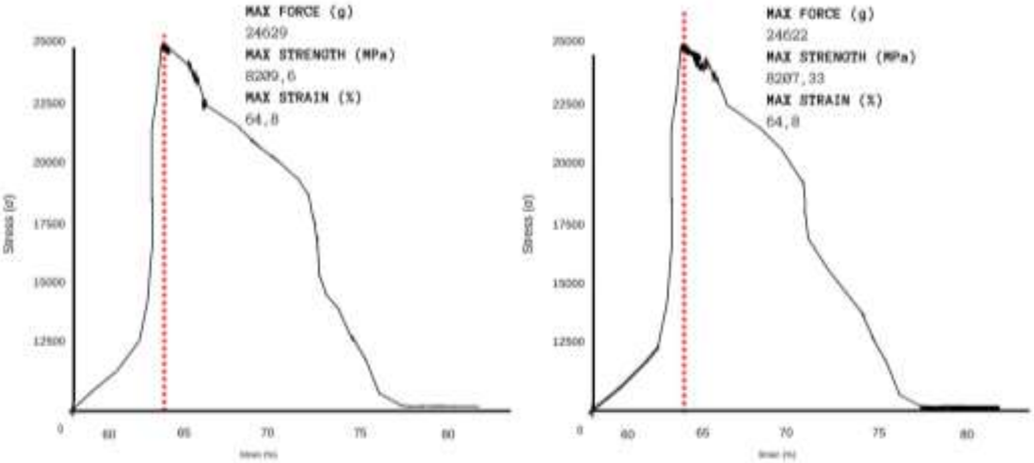

Figure 46. Stress-strain graphs for jBC2.2 and jBC2.3

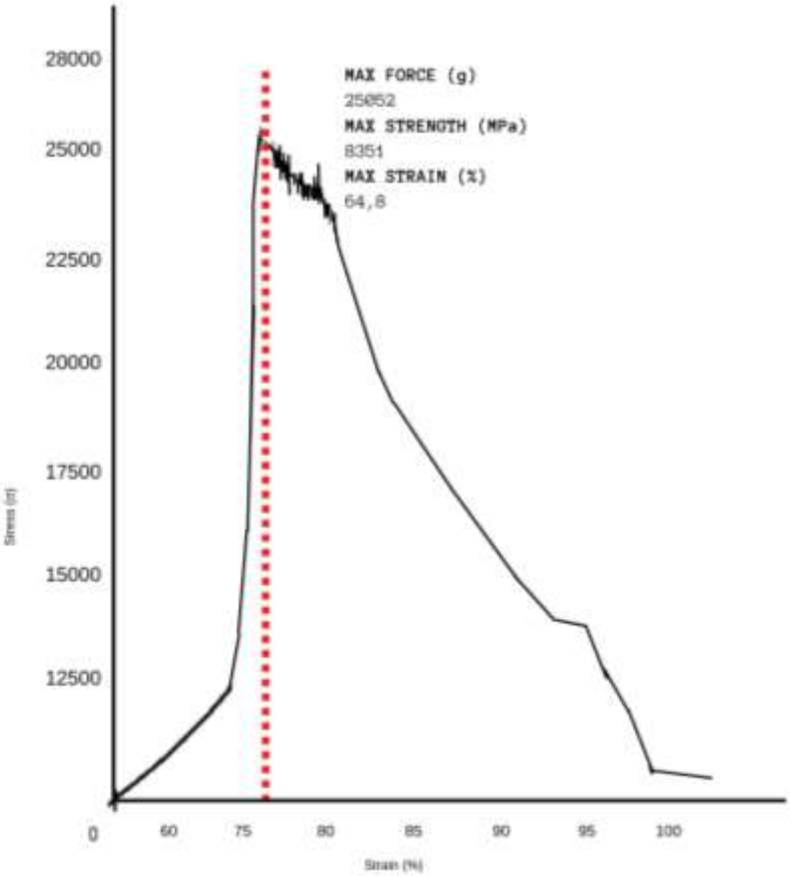

Figure 47. Stress-strain graph for jBC3.1 (max.)

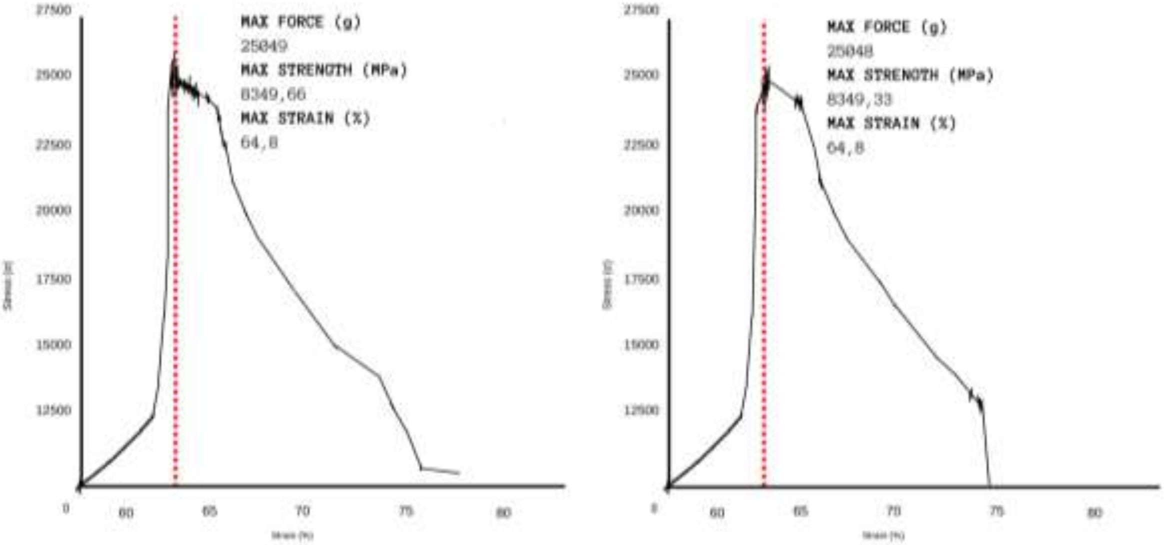

Figure 48. Stress-strain graphs for jBC3.2 and jBC3.3

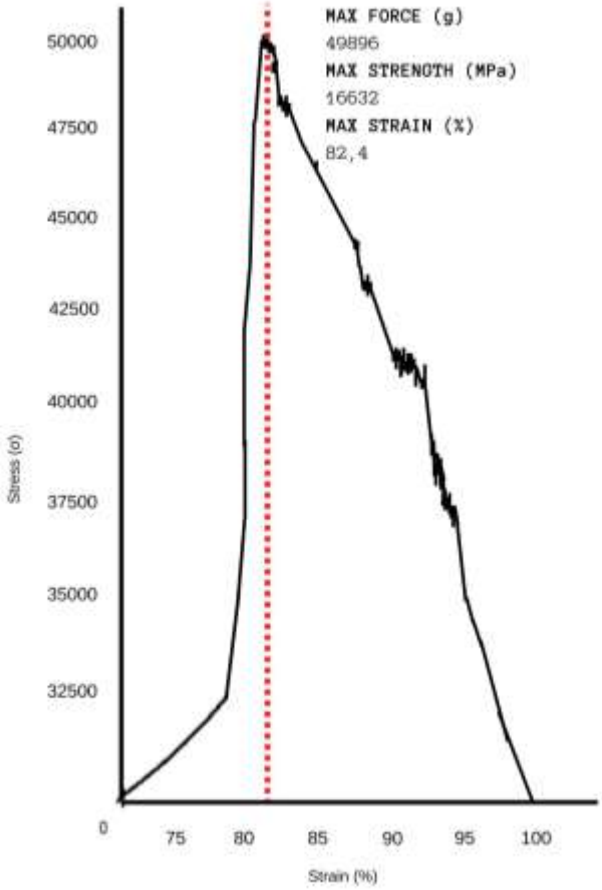

Figure 49. Stress-strain graph for jBC4.1 (max.)

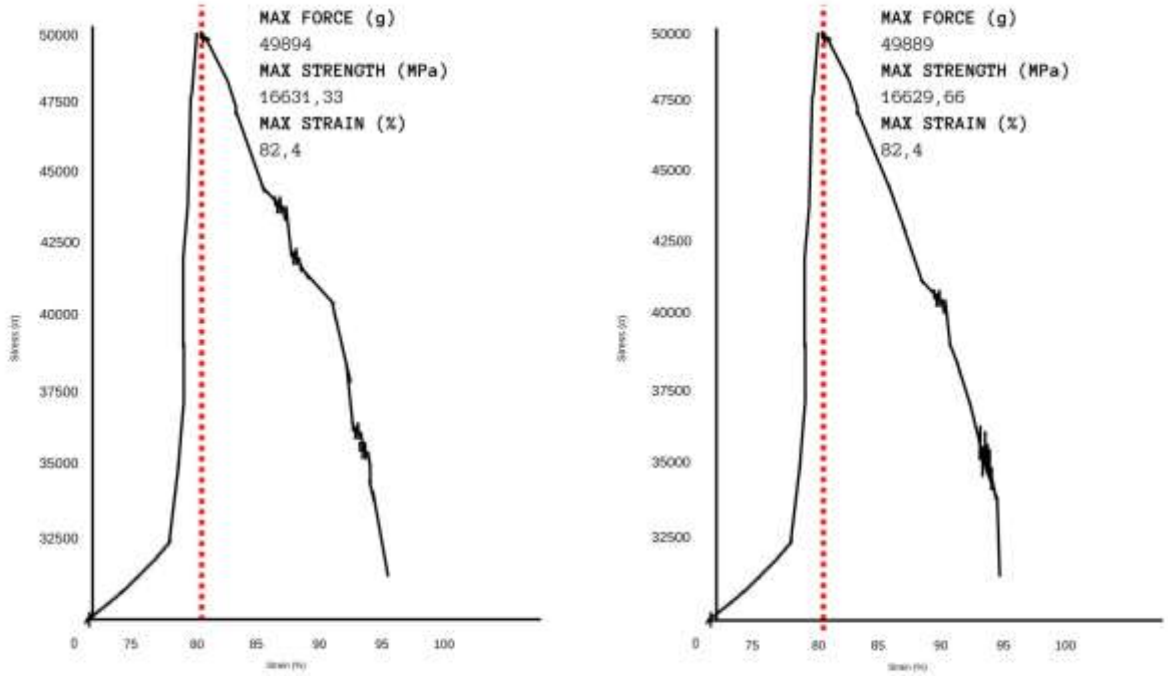

Figure 50. Stress-strain graph for jBC4.2 and jBC4.3

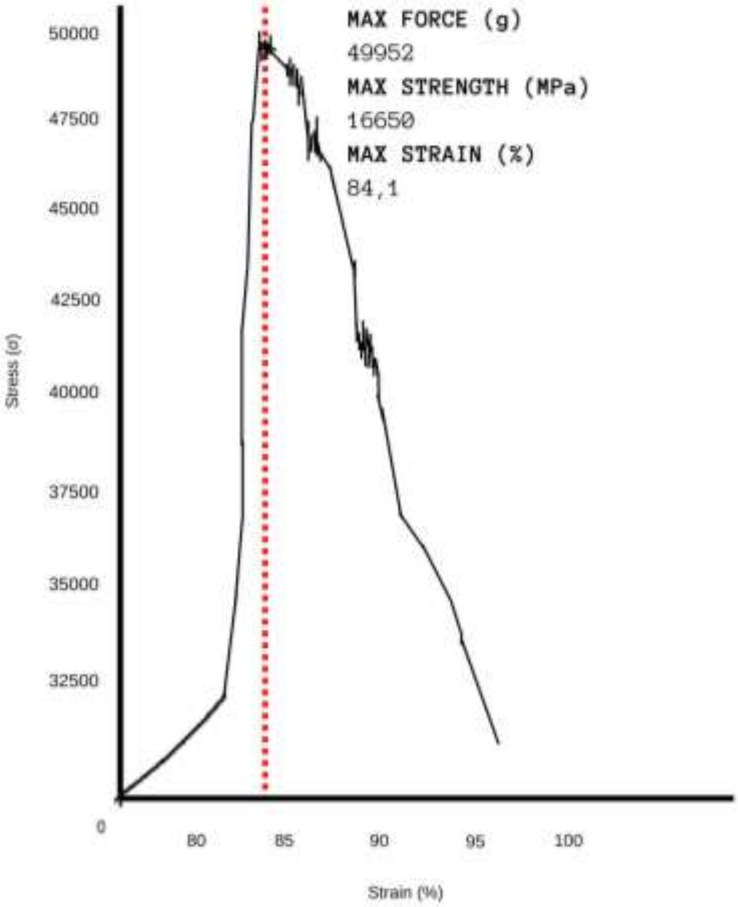

Figure 51. Stress-strain graph for jBC5.1 (max.)

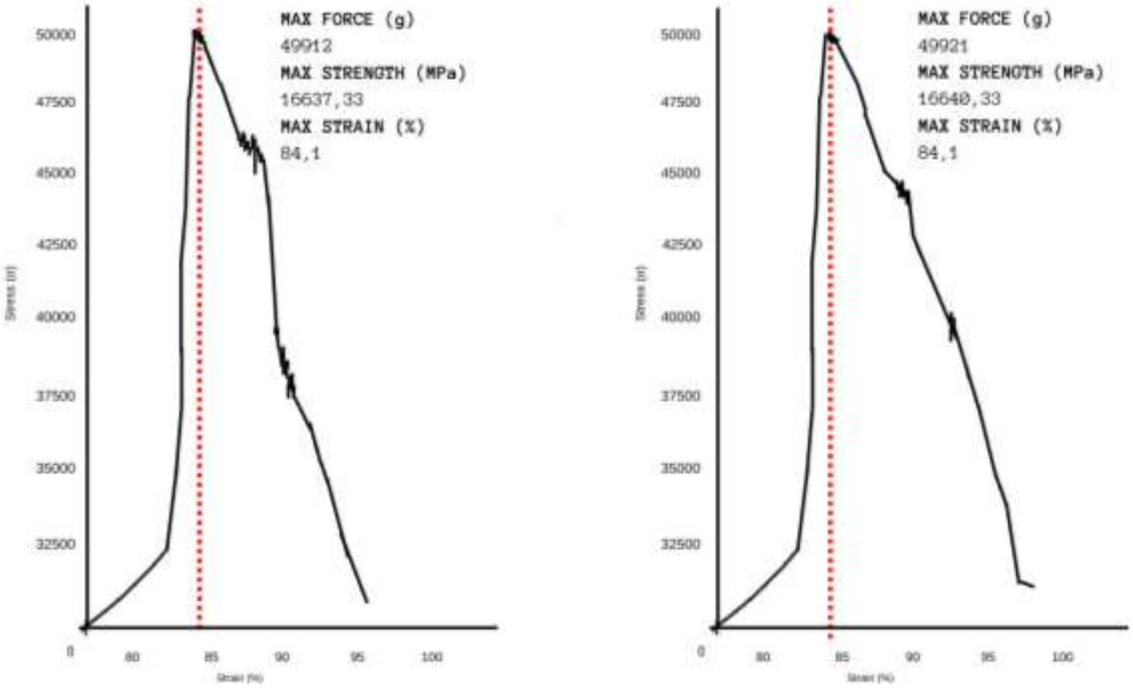

Figure 52. Stress-strain graph for jBC5.2 and jBC5.3

3.5. Integration of mechanical data to computational form-finding

The design and fabrication of complex geometries requires a form-finding process in which the parameters are structured to determine the optimum geometry addressing a static equilibrium of various forces such as the self-load, gravity and other reaction forces (Adriaenssens et al., 2014). Antoni Gaudi's chapel for Colonia Guell and arches for the Casa Mila exemplify the principles of form-finding processes for hanging catenary structures (Huerta, 2006). After the 1950s, catenary structures were studied further through physical models in terms of thicknesses and placement of reinforcements although the quantitative analysis was missing (Naboni, 2016). Unlike the rope with two support points, these hanging structures have complex networks in which they end up with multiple formations. The reason is that the ways of load distribution might differ for each case (Ochsendorf and Block, 2014).

Predominantly, catenary geometries suggest various possibilities for self-standing structures. These tension-only structures are capable of finding their own optimum form under given forces. After they reach the right form, the structure can be turned upside down in order to obtain a compression-only structure (Naboni, 2016). In other words, once it's reversed, it should be able to keep its form rigid. Within the context of this dissertation, the structural form-finding exploration of BC and its derivative composites were simulated and analyzed through catenary geometries since the BC biofilm and composites have high tensile properties. Therefore, catenary geometries that work well in tension are considered a reliable match.

3.5.1. Conventional workflow

Within the scope of this dissertation, based on Gaudi's idea on tension-only structures and reversed compression-only structures, a catenary geometry was developed through a systematic computational workflow. In order to analyze the catenary geometries, Particle Spring System (PSS) within a genetic algorithm definition was employed for the digital form-finding process in Rhinoceros 3D/Grasshopper, using Kangaroo Physics plug-in.

Computational studies were conducted with a focus on form-finding and structural performance analysis through a generic catenary geometry. After an initial catenary geometry was developed, the inputs and outputs were analyzed. The preliminary simulation underlined that material preference was not one of the parameters for the form-finding of catenary geometries and the optimal form does not change for different materials. Therefore, a customized definition was developed with the idea of integrating mechanical data into the digital form-finding process. All the processes were then adapted for three types of composites.

Kangaroo Physics' solver component and other complementary components were investigated. The solver has seven inputs and three outputs. The inputs involve GoalObjects which has the generic data, Reset that completely rebuilds the particle list and indexing, Threshold that is to stop the solver when average movement is less than the given value, Tolerance that is for combining the points closer than the given distance into a single particle, Damping that determines for how much velocity is preserved between iterations, Iterations determines how many internal iterations will be performed for each results output and On (a boolean operator) that makes the solver continue to iterate until it reaches the given threshold value (Table 13). The outputs have I, V and O which respectively signify iterations, vertices and GoalFunction outputs (Table 14). Strength parameter depends on the elastic modulus. The unit was required to be set as meters and GPa. Therefore, tensile strength values obtained from tests were converted from MPa to GPa.

Table 13. Kangaroo's solver input variables

Name	**ID**	**Description**	**Type**
GoalObjects	GoalObjects	GoalObjects	Generic Data
Reset	Reset	Hard Reset (completely rebuild the particle list and indexing)	Boolean
Threshold	Threshold	Stop when average movement is less than this (default is 1e-15)	Number
Tolerance	Tolerance	Points closer than this distance will be combined into a single particle	Number
On	On	If true, Kangaroo will continue to iterate until reaching the given threshold value	Boolean

Table 14. Kangaroo’s solver outputs

Name	ID	Description	Type
Iterations	I	Iterations	Integer
Vertices	V	Vertices	Point
Outputs	O	GoalFunction Outputs	Generic Data

In order to better understand the terminology of Kangaroo, with the use of the above component and other complementary inputs and outputs, a simple curve that behaves as a bending fiber was created and its behavior was observed with the existing definition (Figure 52). First, a start point and an end point was defined. A curve was created between these points and its length data was derived. A catenary was created through that curve and direction of gravity, loads and location of two anchor points (start and end point) were assigned. Finally, the solver component was run to simulate the behavior of the 2D geometry.

Although a simple curve and its bending behavior as a catenary geometry give us hints about how to use Kangaroo Physics data together with mechanical data, a form finding process was conducted in 3D in order to explore the response of such data in mechanical engineering terminology and which data sets Kangaroo Physics provides and needs for a precise simulation. Therefore, the dataset created based on the tensile tests was provided for the catenary geometry.

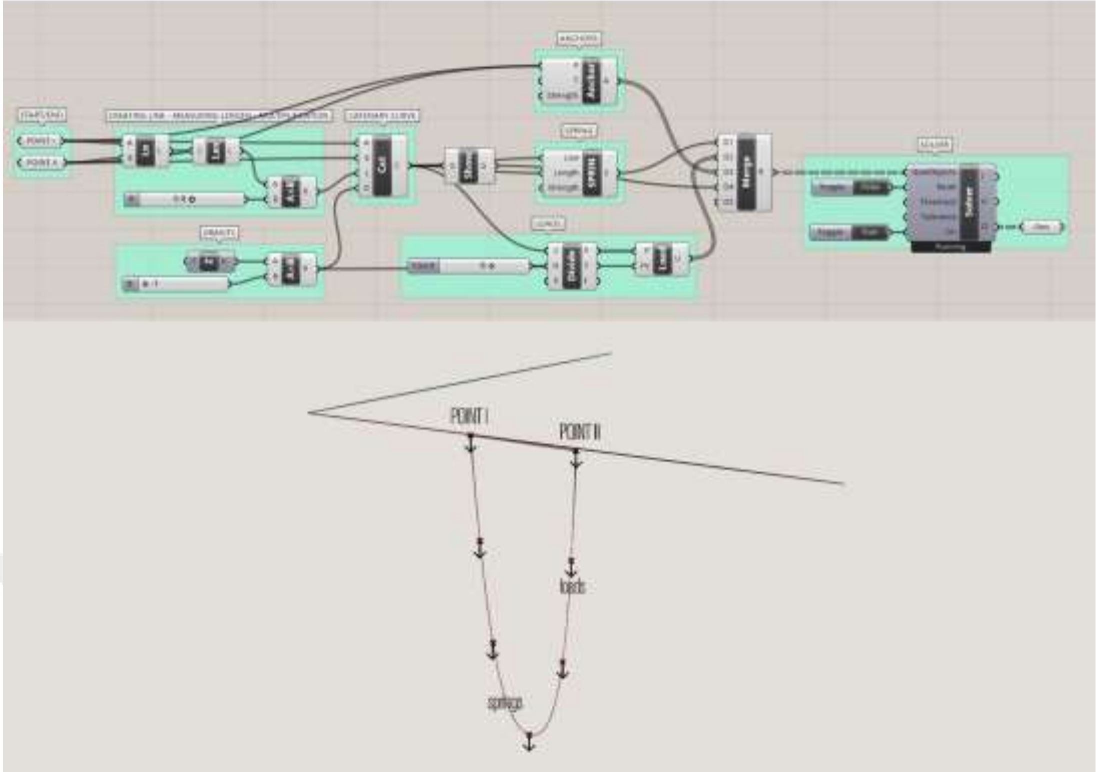

Figure 52. Simple catenary curve definition on Kangaroo Physics, Grasshopper

Within the context of this study, a 3D catenary geometry was developed to evaluate the mesh topology by following the conventional workflow (Figure 53). The constraints such as the gravity, loads, and anchors were the initial inputs for the optimization procedure without defining any specific material or composite origin, in a way, validating the software deficiency to fully simulate the material behavior (Figure 54).

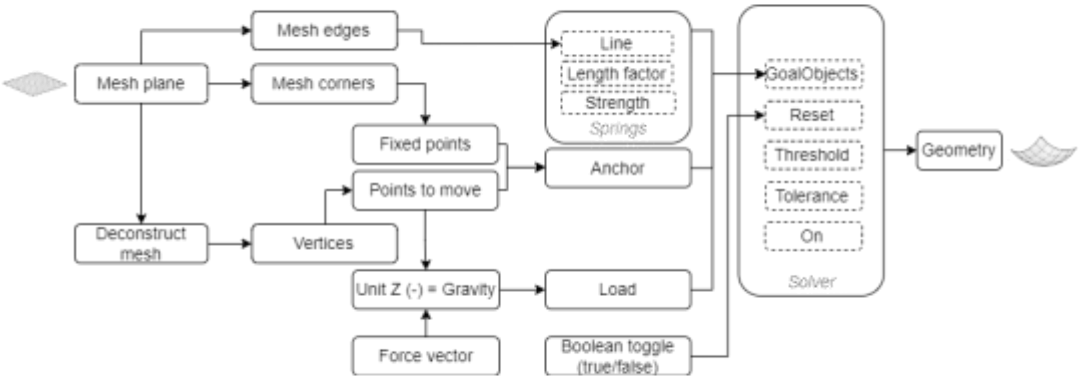

Figure 53. Conventional workflow for a catenary geometry

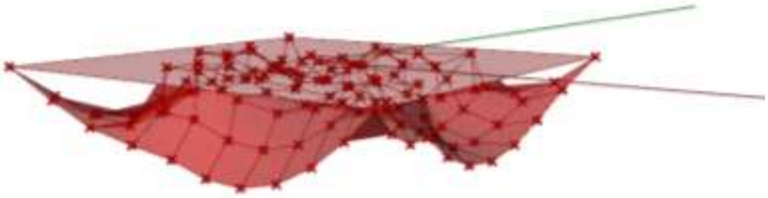

Figure 54. An initial 3D catenary geometry generated for a generic bending material

3.5.2. Mechanically-informed workflow

The underlying approach for this dissertation was the use of digital and mechanical workflows to benefit from the self-organization ability of the elastic material under certain forces in equilibrium. Therefore, the form had to have originated from a balance of external forces and mechanically inherited material properties. That is why, the computational form-finding process was informed by the tensile test results in order to optimize the geometry in relation to the form and the material.

Although material behavior in Kangaroo Physics is rather non-linear, the modulus of elasticity, thus stress, strain, and other values associated with it, can be introduced into Kangaroo to achieve a more accurate form-finding simulation. Kangaroo's solver component and other complementary components were explored in order to incorporate the collected data from tensile testing into the digital structural optimization and form-finding process, and the generic definition was manipulated in order to simulate the behavior of cBC, bBC, jBC composites. The materials were introduced with the loads including the dead load of bacterial cellulose and native fibers. The total geometry was constrained within a 10mx10mx10m bounding box, simulating at 1:1 scale. The manipulations include the introduction of material properties and stochastic distribution of multiple anchor points (Figure 55). The interface displayed the values for deflection, tensile stress lines, and bending moment for each mesh component.

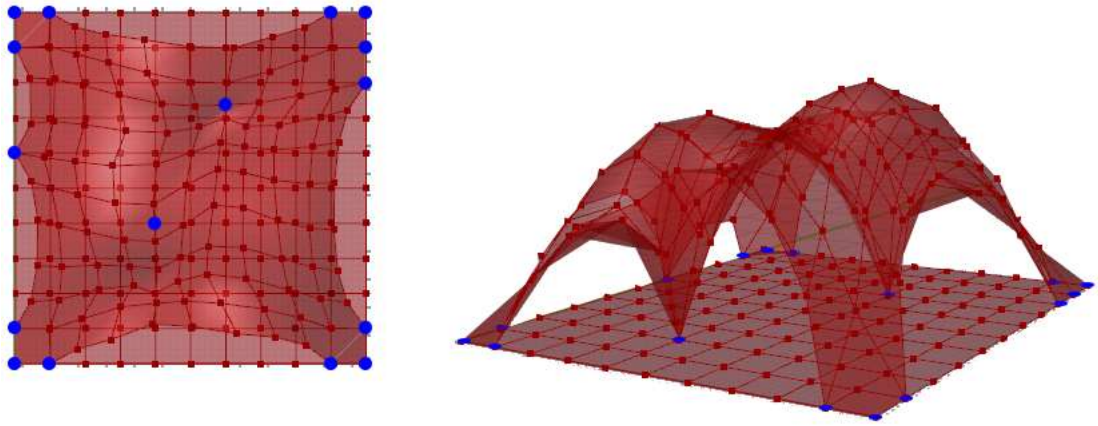

Figure 55. The bounding box and stochastic selection of anchor points

In order to introduce the material properties into Kangaroo, Newton’s and Hooke’s laws were used through mathematical expressions in Grasshopper. The Expression component (Figure 56) is an extremely adaptable tool that could be utilized in a wide range of scenarios by adopting mathematical algorithms and producing quantitative results.

```
Format("{0}, {1}", x, y)
```

Figure 56. Expression component in Grasshopper to introduce the relation of two inputs

First, Newton’s second law was used to introduce a mass for each spring, mobile nodes, and anchors (Figure 57). Secondly, the initial length of the mesh edges provides L_i for each edge [$F=k(L_0-L_i)$]. Similarly, in the equation of [$L_0=a*L_i$], "a" indicates the length factor, and "k" represents the stiffness of the connection. Stiffness could be computed using the equation [$(E*S/L_0) = k$], derived from Hooke's law (Figure 58). [$R_e = F_e/S$] expression simulates where yield strength (Pa) is exceeded. Additionally, another calculation was performed using the modulus of elasticity equation: [$F=E*S(L/L_0-1)$] in order to compare the ratio of force (F) to maximum force (F_e) for verifying the simulation (Figure 59). Besides the flowchart, the visuals on Grasshopper canvas is also given in Figure 60 below.

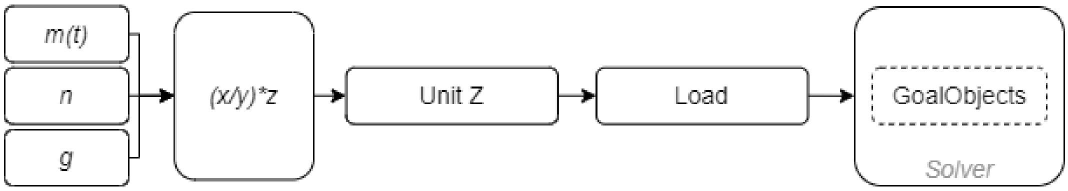

Figure 57. Newton’s law for introducing weight and mass of goal objects (springs, mobile nodes, anchors)

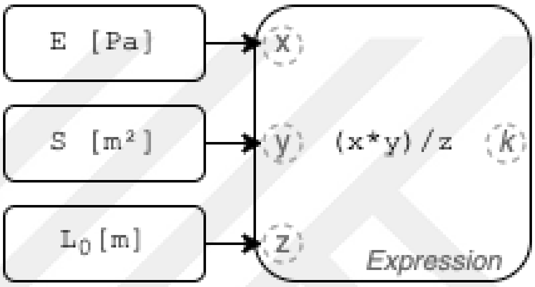

Figure 58. Definition for stiffness calculation following Hooke’s law [(E*S/L_0) = k]

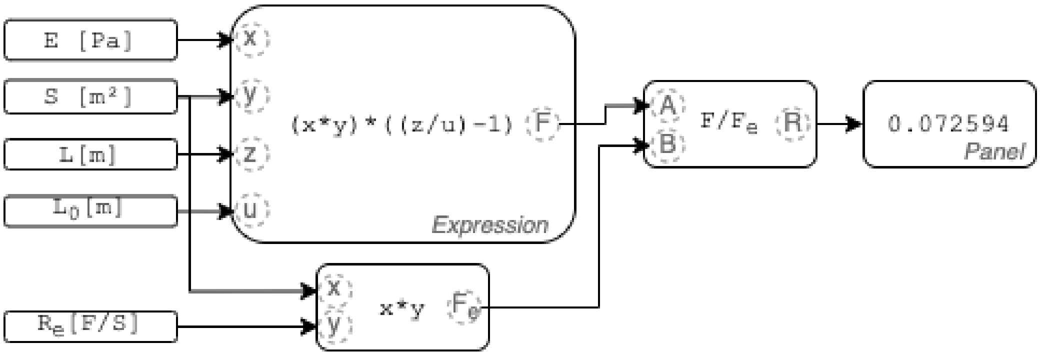

Figure 59. Yield strength calculation and verification of simulation based on elasticity

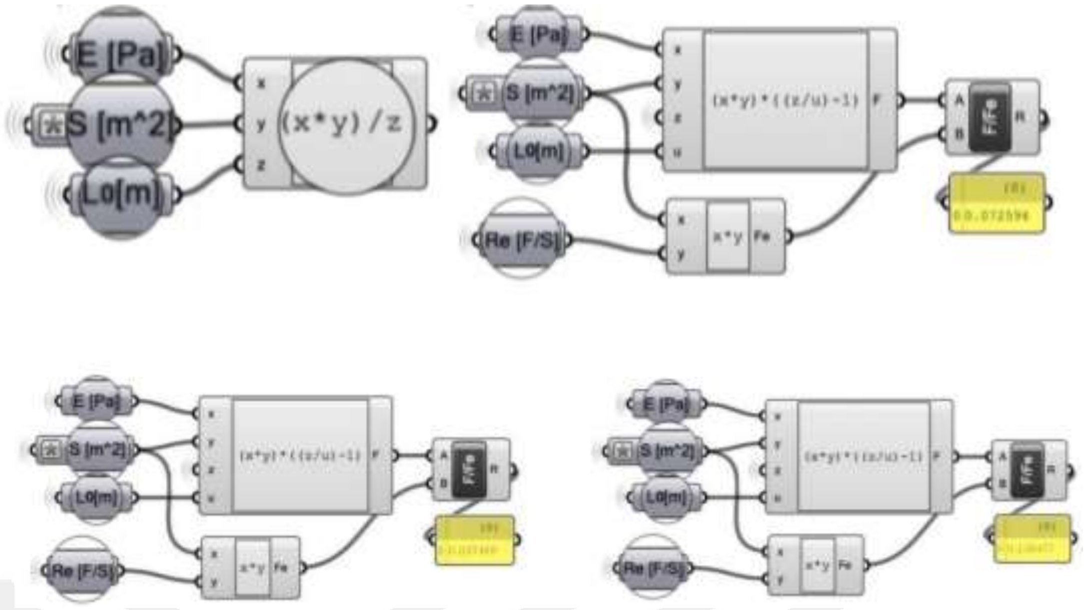

Figure 60. Definition for stiffness calculation (upper left), yield strength calculation for jBC (upper right), for cBC (bottom left) and bBC (bottom right) on Grasshopper canvas

If F/F_e is between 0 and 1, the deformation is elastic, indicating that the simulation is valid. If this value is more than 1, the material is under plastic deformation, and thus the simulation fails. The resulting value could be seen with the panel component. After the data convergence for digital form-finding, the simulations for each composite resulted in a value between 0 to 1, therefore, indicating an elastic behavior.

Based on the results of the simulations conducted using Kangaroo, it was found that all of the composites (uBC, cBC, bBC, jBC) have the ability to withstand forces without undergoing permanent deformation. It is interesting to note that cBC5, bBC4, and jBC4 had the highest tensile strength values among the composites tested. This suggests that these particular composites may be the most suitable for use in structural applications where high tensile strength is required. However, further research is needed to fully understand the behavior of these materials under different loading conditions and to determine their optimal usage in various structural applications.

The integration of physical and digital workflows in this dissertation has allowed for a more accurate and precise form-finding process for these biobased composite materials. By introducing specific material properties into the digital simulations, it was possible to obtain results that more accurately reflected the behavior of the materials in reality.

Overall, this dissertation has demonstrated the potential of using biobased composite materials, such as uBC, cBC, bBC, and jBC, in structural applications. Further studies are needed to fully understand the capabilities and limitations of these materials; however, the results provide a promising starting point for the development and utilization of these sustainable materials in the built environment.

The results revealed a difference in simulating the form-finding process of biobased materials through introducing a generic bending material versus introducing specific material properties (Figure 61). Although the simulations were justified, calculating the modulus of elasticity for BC and composite derivatives is still challenging since the modulus of elasticity is usually a constant value that is predefined in the literature for various types of materials such as metals, plastics, concrete etc. The value for BC biofilms fluctuates depending on the assembly order, growth medium, and conditions of processing, including the measurement of temperature and humidity (Hu et al., 2011). However, by sorting the mechanical data, many of the material properties can be defined, calculated, and derived to have a more accurate simulation in the digital media.

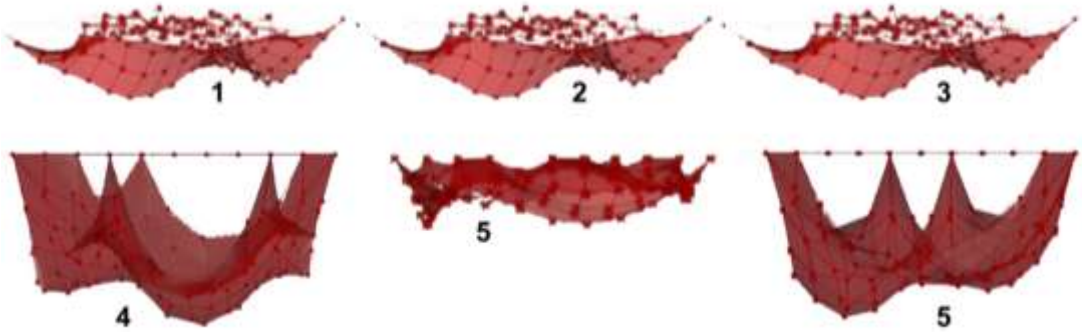

Figure 61. 1-2-3: Computational form-finding results for generic bending material, 4-5-6: Mechanically-informed computational form-finding for jBC, cBC, and bBC composites

3.5.3. Comparative results and evaluation

In the mechanical to the digital integration process, the generic description of a catenary geometry was manipulated in order to integrate data from tensile testing. Unlike the digital-alone structural optimization approach, it was seen that the digital optimization applied to three different composites demonstrated different results. Without integrating tensile testing information into Kangaroo Physics, the optimization process for three different types of composites resulted in very similar structural capacity and form.

The three composite cases demonstrated the integrated model's accuracy as well as its potential at bigger scales with higher degrees of complexity. It showed its potential to enable designers to achieve a higher degree of precision in form-finding with Kangaroo or similar digital optimization tools by mediating between each step of whole technical complexity, through the physical and digital simulations. This dissertation can also be considered as the beginning point for adding further physical features, in addition to considering large-scale applications of biologically active materials.

In our fast-paced digital age, digital media and the algorithms they rely on are often represented through simplified interfaces, causing designers to sacrifice a certain amount of control over their practices. This dissertation is also considered as an attempt to give architects and designers back control by reducing the information asymmetry between the mechanical testing of the physical model and the digital model, considering the novel materials’ unique properties.

CHAPTER 4: CONCLUSION AND DISCUSSION

In this dissertation, the main goal of this dissertation was to improve the accuracy and effectiveness of computational form-finding tools such as Kangaroo in the design process for composites. In order to do this, a method for integrating data from tensile testing, which is a type of mechanical testing used to measure the strength and behavior of materials under tension was developed into an integrated computational form-finding process. This was achieved through the manipulation of a generic description of a catenary geometry, which is based on a catenary curve that a hanging chain assumes under its own weight.

An integrated approach was developed to optimize the fabrication-aware design of three different composites, and compared the results to those obtained using a digital-alone optimization approach. It was seen that the integrated approach resulted in more accurate and diverse results, demonstrating the potential for use on larger, more complex systems.

Through the use of mechanical testing and computational form-finding with Kangaroo Physics, it was demonstrated that the incorporation of specific material properties greatly affected the resulting structural capacity and form of the three different composites, cBC, bBC, and jBC. This suggests the potential for designers to achieve a higher degree of precision in their structural designs by utilizing both physical and digital simulations, and mediating between the two through the integration of mechanical testing data.

One of the key benefits of this integration is that it allows designers to take into account the unique properties of the materials being used, which can be difficult to do using digital-alone approaches. This is particularly important in the design of composites, where the combination of different materials can significantly impact the overall performance of the final product. By reducing the information assymetry between the physical and digital models, designers can make more informed decisions and achieve a higher degree of precision in form-finding considering the materials' unique properties.

The dissertation also addressed the lack of a systematic framework and a database for the form-finding of biobased materials and composites. By conducting tensile tests and comparing the results of uBC, cBC, bBC, and jBC, it showed promise and feasibility for using BC-based composites in potential structural applications. It was found that the best performing composites in terms of tension were cBC5, bBC4, and jBC4, which had higher tensile strength values and required less material. In addition, using higher density cotton or alternative fibers such as bamboo or jute can be necessary in cases where higher tensile strength values are required.

Overall, the results of this dissertation demonstrate the potential for using digital form-finding and mechanical testing to optimize the design and fabrication of complex geometries made from BC and its derivative composites. While the modulus of elasticity for BC and its derivative composites remains a challenge due to fluctuations in its value, this dissertation presents a starting point for adding further physical features and considering large-scale applications of other biologically active materials. By considering the unique properties of these biobased materials, it is possible to achieve a higher degree of precision in form-finding and ultimately, design more efficient and sustainable structures.

Considering the developments in artificial intelligence, design space tends towards digitalization. Although developing technologies enabled designers to overcome the effects of the Anthropocene in a more sustainable way than ever before in terms of material development, there is an information asymmetry between design and manufacturing as well as academia and industry.

In this dissertation, an integrated framework was proposed to highlight both the interdependencies between two prominent disciplines -mechanical engineering and computational design, and the necessity for a holistic approach towards the form-finding of biobased materials and composites with a case study on bacterial cellulose and composites. Mechanically-informed bacterial cellulose-based catenary geometries demonstrated that such an integrated workflow questions whether we can construct structures that are not threats to the environment by designing materials out of literally nature by nature’s own algorithms adapted to digital media, and by constructing a bridge with the material itself and digital form-finding processes.

In terms of future studies, this dissertation envisions a space where the living matter acts as an active component, which continues to perform biological functions such as self-regeneration, neutralizing dangerous chemicals or transforming carbon dioxide and releasing oxygen. These types of systems require high liquid content that allows the transmission of signals between living cells which is a challenging achievement.

There are also some other conditions to sustain life for living matters, such as a self-supportive structure system or a circulation path to allow liquids or hydrogels to go in and out. These requirements can be enhanced to create even more beneficial results when combined with a system design for feedback, allowing living matter to process information and adapt its behavior or the integration of biological sensors, engineered to become an interface for the living matter to respond to the environmental conditions. This requires another collaboration from disciplines such as bioengineering, chemical engineering and electrical engineering.

Although the results of the experiments are quite promising, after all, a wider application of bacterial cellulose is consequently linked to the practical factors and parameters such as the large-scale buildability and production approaches, therefore digital fabrication methods, or carbon and nitrogen sources and bacterial species within different cultures, and even fermentation equipment and tools should also be further investigated. Despite the limitations, in overall, this dissertation represents an important step forward in the integration of mechanical and digital processes, and has the potential to improve the efficiency and effectiveness of design processes in a variety of fields.

As the spin-off projects, different scales of designing and fabricating with bacterial cellulose were explored. The first one was “3D Printing with Bacterial Cellulose-based Bioactive Composites for Design Applications” (Turhan et al., 2022). The research was presented to an international audience at the 40th Conference on Education and Research in Computer Aided Architectural Design in Europe (eCAADe 2022). The focus was on the BC biofilm cultivation and printable composite formulation to design and fabricate a plant pot as an industrial product. As a result, an improved interfacial adhesion for the composite by incorporating natural fibers resulted in improved mechanical properties, which was implemented by modifying the matrices. It was observed that the structural integrity was well achieved since none of the materials within the composite could stand against its own weight alone but the composite showed its integrity without liquid content removal (Figure 62).

Figure 62. Enhanced structural integrity by creating matrices with fillers and gelling agents

The other project was Harvesting Biofabrics (Figure 63), a living textile collection that was exhibited at a national curated exhibition, Good Design Izmir-7, as one of the invited projects. This research explored the potential of BC as a living fabric for a circular fashion design. The 3D modeling, laser-cutting, assembly of a fashion dummy, a scaffold design for the bacterial cellulose layer, biobased material formulation, and bio-assembly were the explored aspects of the project.

Figure 63. Harvesting Biofabrics, Good Design Izmir_7, Izmir/Turkey

The other potential future works can include:

1. The transformation of the suggested framework into an open-source plug-in to be used on Kangaroo Physics or on Grasshopper can be one option to make the proposed framework more widely accessible and user-friendly by developing

it into an open-source plugin that can be integrated into existing design workflows using Kangaroo Physics or Grasshopper. This would allow other researchers, designers and engineers to easily apply the methods and techniques developed in the dissertation to their own work.

2. Another potential future work can focus on the full scale physical applications to further investigate the potentials and to see deficiencies to optimize and further develop. This future work can test the proposed framework and techniques at a full scale in real-world applications to evaluate their performance and identify any deficiencies. This would help to optimize the methods and techniques and further develop them for practical use.

3. Engineering the bacteria to produce more resilient cellulose layers could be another option to improve the mechanical properties of bacterial cellulose further by engineering the bacteria. Isolating the genes that producing the cellulose into more productive bacteria by adopting the recombinant protein technology, we can introduce genes encoding the enzymes responsible for producing bacterial cellulose into other bacteria, such as E. coli. This would allow for large-scale production of bacterial cellulose, which has potential applications in a variety of industries, including the production of biofuels, textiles, and food products. This could also potentially lead to stronger and more durable biobased materials for use in design and fabrication.

4. Investigation on different composite formulations could explore the potential of using bacterial cellulose or other biobased materials in conjunction with other reinforcement or colorant materials, including natural dying. This could lead to the development of new, high-performing biobased composites with unique aesthetic properties for use in design and fabrication.

5. Investigations on different design scales such as industrial products, garments or architectural pavilions could explore the potential of the proposed framework and techniques for use in different design scales and fields, such as industrial products, garments or architectural pavilions. This would help to

understand how the methods and techniques could be applied to different types of design problems and applications.

6. Repeating the same procedure for the other biobased materials and composites could aim to extend the study to other biobased materials and composites, to understand the generalizability of the proposed framework and techniques, and identify any potential limitations or challenges. This would allow to expand the options of biobased materials available for design and fabrication, as well as to better understand their properties and behavior.

7. Creating a global database for the material properties of biobased materials and composites for design applications with the aid of large language models (LLMs) and/or text-to-image based diffusion models can contribute to the creation of a comprehensive database of material properties for biobased materials and composites that can be used in design and fabrication, by leveraging the power of large language models (LLMs) and/or text-to-image based diffusion models to gather, process and organize the data. This database would allow designers and engineers to easily access information on the mechanical and physical properties of different biobased materials, making it easier to select materials for specific design projects and also it will help to improve the accuracy and efficiency of the data collection and visualization processes.

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APPENDICES

Appendix A – Curriculum Vitae

Dr. Turhan graduated from the Izmir University of Economics, Department of Architecture (B.Sc-hons.) in 2014. She completed the Master in Advanced Architectural Design (M.Arch.) program in Fall 2016 with a focus on scripting languages in architectural design processes, natural algorithms and interactive cities; and Master of Science in Architecture (M.Sc.) program in Spring 2016 with a focus on time-space compression and its effects on global urban space. She studied Ph.D. in Design Studies with a specific focus on biobased material studies, computational design and digital fabrication. Her current interests also include machine learning (ML), diffusion models (DMs) and large language models (LLMs) for design applications. She has been working as a Research Assistant at the Department of Architecture, Faculty of Fine Arts and Design, Izmir University of Economics since September 2017.

Appendix B – Ethical Board Approval

SAYI : B.30.2.İEÜ.0.05.05-**020**-*128* 28.04.2021

KONU : Etik Kurul Kararı hk.

Sayın Gözde Damla Turhan,

“Mechanically-Informed Digital Optimization for Bacterial Cellulose-Based Catenary Geometries” başlıklı projenizin etik uygunluğu konusundaki başvurunuz sonuçlanmıştır.

Etik Kurulumuz 19.04.2021 tarihinde sizin başvurunuzun da içinde bulunduğu bir gündemle toplanmış ve projenin incelenmesi için bir alt komisyon oluşturmuştur. Projenizin detayları alt komisyon üyelerine gönderilerek görüş istenmiştir. Üyelerden gelen raporlar doğrultusunda Etik Kurul 28.04.2021 tarihinde tekrar toplanmış ve raporları gözden geçirmiştir.

Sonuçta 28.04.2021 tarih ve 120 numaralı **“Mechanically-Informed Digital Optimization for Bacterial Cellulose-Based Catenary Geometries”** konulu projenizin etik açıdan uygun olduğuna oy birliği ile karar verilmiştir.

Gereği için bilgilerinize sunarım.

Saygılarımla,

Prof. Dr. Elvan Özkavruk Adanır