Behavior of a Silkworm Silk Fiber Web Structure under Wind Load

By

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Submitted to the Department of Civil and Environmental Engineering on May 19, 2015 in Partial Fulfillment of the Requirements for the Degree of Master of Engineering in Civil and Environmental Engineering

ABSTRACT

Optimized by Nature for millions of years, silk is one of the strongest biomaterials with outstanding mechanical properties, it is both extensible and tough in order to ensure specific functions. In particular, protein-based Bombyx mori silkworm silk’s stiffness is originated from the crystalline region of the semi-crystalline fibroin and the extensibility from the length hidden within the amorphous region. The silk fiber is coated with sericin which acts as a glue connecting fibers together and as a matrix in the three-dimensional nonwoven multi-layer composite structure of the cocoon. These properties can be engineered and enhanced with forced reeling silk: fast spun silks are stiffer and less extensible than slow reeled silk.

For this study, two-dimensional single cocoon layer webs are created by silkworms and tested under an increasing wind load until failure, the deflections are recorded. To complement the experimental results, the web’s structure is generated in two different models: straight fiber web and wavy fiber web models. Both models are studied under constant wind load for four type of fibers with different reeling speeds thus different mechanical properties.

These tests indicate that the deflection increases with wind load for both the experiments and the simulations, but also that webs composed of fibers with different mechanical properties are not necessary stiffer and less extensible as the material they are composed of are stiffer and less extensible because of the high redundancy and randomness of the web structure. The divergence in results between the experiments and the simulations suggests the need to improve the models to be more in accordance with the real webs.

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# Table of Contents

**Abstract** .................................................................................................................................................. 3

**Acknowledgement** .................................................................................................................................. 5

1 **Introduction** ........................................................................................................................................... 9

1.1 Motivations ............................................................................................................................................... 9

1.2 Purpose of the Study ................................................................................................................................. 10

1.3 Outline ...................................................................................................................................................... 10

2 **Background and Literature Review** ........................................................................................................ 11

2.1 Proteins .................................................................................................................................................... 11

2.1.1 Primary Structure ................................................................................................................................. 11

2.1.2 Protein Folding .................................................................................................................................... 11

2.2 Silkworm Silk ......................................................................................................................................... 12

2.2.1 Silkworm: Bombyx mori ...................................................................................................................... 12

2.2.2 A Semi-Crystalline Fiber ..................................................................................................................... 13

2.2.3 Mechanical Properties of Silk ............................................................................................................ 14

2.2.3.1 Synthetic Silk ..................................................................................................................................... 15

2.2.3.2 Forced Reeling .................................................................................................................................. 15

2.3 Cocoon Structure ..................................................................................................................................... 17

2.4 Artificial Structures ................................................................................................................................. 18

3 **Computational Tools and Methodology** ............................................................................................... 21

3.1 Computational Tools ................................................................................................................................ 21

3.2 Methodology ............................................................................................................................................. 22

3.2.1 Experiment .......................................................................................................................................... 22

3.2.1.1 Creation of the single layer silkworm silk web ................................................................................. 22

3.2.1.2 Experimental test ............................................................................................................................... 23

3.2.2 Simulation ............................................................................................................................................ 25

3.2.2.1 Model .............................................................................................................................................. 25

3.2.2.1.1 Straight fiber web ........................................................................................................................... 25

3.2.2.1.2 Wavy Fiber web ............................................................................................................................ 27

3.2.2.2 Simulation experiment ...................................................................................................................... 28

3.2.2.2.1 Wind load experiment .................................................................................................................... 28

3.2.2.2.2 Deflection measurements ............................................................................................................. 31

4 **Experimental Section** ............................................................................................................................ 33

4.1 Experiment .............................................................................................................................................. 33

4.1.1 Method ................................................................................................................................................ 33

4.1.2 Results ................................................................................................................................................. 34
1 Introduction

1.1 Motivations

Natural and biological materials are able to adapt and optimize their structure while having limited resources. Evolution made them develop high-performance mechanical properties designed and optimized to ensure specific functions. With such extraordinary properties, natural and biological materials have been an inspiration for scientists and engineers. Understanding natural materials at every scale, could lead to the creation of new biomimetic efficient materials [1].

Natural silk is such a material. Optimizing their structure for millions of years, silks, such as spider silk or silkworm silk have developed impressive mechanical properties. They have both extensibility and toughness. As one of the strongest natural material, spider silk’s toughness can be as high as Kevlar’s thanks to its extensibility [2,3]. Although weaker than spider silk, silkworm silk’s mechanical properties can be enhanced by artificial reeling. By drawing the silk from a fixed silkworm at different speed, it is possible to design stronger, stiffer and more extensible silkworm silk which can be compared with spider silk [4].

Natural silk structures such as spider webs and cocoons are also highly tuned structures optimized by evolution. Indeed, spider webs as discrete structures, are stiff enough to withstand the weight of the spider and its prey while absorbing energy from external loads such as wind or the impact of the prey [5]. Engineered by Nature, silkworm cocoons have developed a light and resilient multi-layered structure in order to protect the pupae from environment and animal threats, such as impacts and attacks [6,7].

Inspired by both two dimensional spider orb webs and cocoon layers, a single cocoon layer silkworm silk was naturally fabricated, by silkworms, into a two dimensional web and studied under wind load.
1.2 PURPOSE OF THE STUDY

The purpose of the study is to investigate the behavior of this biomimetic structure under wind load by comparing physical experiments with their simulations. This study will provide a better understanding of the relationship between the properties of the material, the silkworm silk, and the properties of the structure, the single-layer silkworm silk web structure.

1.3 OUTLINE

The study describes the behavior of this nature-inspired cocoon layer web structure under wind load. The thesis is organized as follows: Chapter 2 introduces knowledge on the mechanical properties of silk, from the nanoscale, with the protein sequence to the macroscale with its cocoon structure. Chapter 3 outlines the computational tools and describes the geometry of the single cocoon layer web, the procedure used to fabricate the physical web and the model. Chapter 4 presents the findings of the experiments in the wind tunnel of the physical silkworm silk web and the simulations of the web under wind load. Chapter 5 summarizes the investigation, provides recommendations for future.
2 BACKGROUND AND LITERATURE REVIEW

2.1 PROTEINS

Natural silk fibers are polymers or proteins which are organic molecules composed of a long chains of amino acids [1,5]. Proteins are defined at different levels by their primary structure which is the sequence of amino acids, the secondary and tertiary structures which is the folding of the chain on itself and the quaternary structure or the arrangement of the several chains [1,8,9].

2.1.1 Primary Structure

Proteins are composed of chains of building blocks, or amino acids ordered in a specific sequence and linked by peptide bonds. The 20 different amino acids can be arranged into an infinite number of different combinations and sequence length, which explains the large diversity of protein functionality [8,9].

2.1.2 Protein Folding

The different properties of the amino acids induce attraction or repulsion of the building blocks within the chain. This phenomenon creates a local folding of the chain, called secondary structure, as shown on Figure 1. The common folded shape are beta-sheets, helices and loops. The next level is the folding of the protein into three dimensional and more compact structures, called tertiary structures. Finally, some proteins organize themselves into even more complex structures [8,9].
In the case of silk proteins, as it is a fibrous protein, it is mainly composed of secondary structures and has an elongated shape [8].

2.2 **Silkworm Silk**

Silks are produced by crustaceans, such as mussels [10], and numerous insects such as spiders and silkworms. The toughest natural silk is the dragline spider silk which is mainly used for the structural threads of the spider web, it has to be strong and stiff enough to withstand the weight of the spider and its prey while absorbing energy from external loads such as wind or the impact of the prey [1,11]. The silkworm silk on the other hand is weaker and not as extensible but its properties can be enhanced by forced reeling [4,6].

2.2.1 **Silkworm: Bombyx mori**

The commercial silk is extracted from Bombyx mori silkworms cocoon culture, or sericulture. Originated from China, Bombyx mori silkworms have been completely domesticated for 4000 years and cultivated for the production of textiles [6,13,14,15]. Also called mulberry silkworms because they feed from mulberry leaves only, they start spinning silk at the fifth and final instar of the larval stage [14,16] to build a cocoon in which they transform into moths. Figure 2 shows a silkworm at the fifth instar ready to spin silk. A continuous silk fiber, up to 1000 meter long, is reeled from the cocoon after boiling it in water, this process is called degumming [15].

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**Figure 1 - Protein sequence and folding.** (a) Schematic protein sequence. The beads represents different amino acids (b) Folding of the sequence. (c) Three dimensional folding. [8]
2.2.2 A Semi-Crystalline Fiber

The silk fiber spun by silkworms is called bave and is composed of two brins which are fibroin fiber coated together with a layer of sericin. The fibroin fibers are proteins composed of a repeating units of the building blocks alanine, glycine and serine arranged in this order: -Gly-Ala-Gly-Ala-Gly-Ser- [12,14]. The proteins mainly fold into beta sheet crystals which explain the strength and the stiffness of fibers. Under tensile load, the beta-sheets, oriented in the length of the fiber, within the protein resist to the shear load and consequently justify the superior mechanical properties of silk [14,17]. The strength and the extensibility of the silk fibers is justified by the semi-crystalline structure of the fibroins. Stiffness is due to the beta-sheet crystals and extensibility is induced by the hidden length of the amorphous part of the fibroin [1,13]. On the contrary, sericin coating is mainly composed of an amorphous and disordered structure which acts as a glue by binding the two fibroins together [14]. Figure 3 shows the hierarchical structure of silkworm silk as different scale.
Figure 3 – Hierarchical structure of silkworm silk. Adapted from [12] and [38].

2.2.3 Mechanical Properties of Silk

Design and optimized by nature, silk’s remarkable mechanical properties have inspired engineers and scientists to design materials with the same or improved properties [1]. Compared to Kevlar and high-tensile steel which have a tensile strength of 3.6 GPa and 1.5 GPa respectively, natural Nephila dragline spider silk breaks at a lower strength at 1.3 GPa [1,2]. However, spider silk is tougher, it can absorb more energy before breakage, because of its high extensibility which can reach 50% to 60% strain until failure [19]. On the other hand, Bombyx mori cocoon silk has lower mechanical properties than Nephila spider silk with 0.5 GPa tensile strength, 15% strain at failure and absorbs $6 \cdot 10^4$ J·kg$^{-1}$, therefore less energy than spider silk with a toughness of $16 \cdot 10^4$ J·kg$^{-1}$ [4].

A way to improve the mechanical properties of silk is by creating synthetic silk or by forced reeling.
2.2.3.1 Synthetic Silk

The mechanical properties of silk take their origins from the folding of the amino acids sequence at the nanoscale. Theoretically, by understanding the relationship of the protein sequence and the folding generated of the silk fiber, the fabrication process and its physical properties, it could be possible to predict and create improved synthetic spider silk to meet the desired properties [2,3]. For example, by changing the sequence by adding more protein units containing beta-sheets, the tensile strength of the spider silk fiber is supposed to be higher [2]. Similarly, recombinant silkworm silk has a slightly greater tensile strength than the native silk [20].

2.2.3.2 Forced Reeling

Silkworm silk is usually collected from cocoons after the sericin coating was removed by boiling water or other chemical process [4,15]. Comparable with spider silk, the silk spinning speed of the silkworm greatly influences its properties. When building the cocoon, the silkworm rotates its head, and accelerates or decelerates whether it is moving from one side to the other side of the cocoon or changing direction. Thus, extracted silk is subjected to irregularities because of the uncontrollability of spinning speed [4]. Nevertheless, this reeling speed can be controlled by pulling the silk from the spinneret of the silkworm at a desired speed after fixing and immobilizing the silkworm [4,12,14,21], as shown in Figure 4. Silk forced reeling method showed that its mechanical properties can be enhanced with faster or slower pulling rate. For instance, by pulling faster, the tensile strength can increase from 0.5 GPa up to 0.7 GPa, though, weaker than spider silk (1.5 GPa). As its extensibility goes down, it toughness also decreases. Oppositely, silk reeled at a slower pace become more extensible with 37% strain at failure and can be compared with spider silk properties [4]. Engineering silkworm silk can improve certain mechanical properties toward the strongest and toughest biomaterial which is spider silk. Figure 5 shows the different stress-strain curves of forced reeled silk at different speeds, compared with spider silk.
Even if forced reeling stabilizes the properties of the silk, there is still variability present along the length of the fiber. One of the difficulties of the reeling process is the unpredictable behavior of the live silkworm, when pulling too fast, the silkworm might resist and break the fiber leading to unpredictable and uncontrollable properties [12]. Even if a single fiber is produced continuously, the section area of the fiber is highly variable because of the different thickness of
the sericin coating along the length of the silk and influences the stress-strain curves [14]. The method to solve this fluctuation is to consider the cross section of the two fibroins instead of the total cross section including the sericin. Thus, the fibroins are structural and carry all the loads whereas the sericin coating only serves as a glue connecting and protecting the fibroins [4,12,14]. The geometry of the fibers are determined with SEM (Scanning electron microscope) micrograph imaging.

2.3 COCOON STRUCTURE

Just as nature tuned silk’s properties, the cocoon was also optimized into the most efficient structure: it has to protect the silkworm from any animal or environmental threats while providing a nurturing environment [7]. Silkworm cocoon is a multilayer structure made of a single continuous fiber. Each layer is formed with loops of silk due to the gyrating or rotating head movements of the silkworm [22,23]. Cocoons are a nonwoven silk composite structure where sericin binds the different layers [6,7,13,15,22]. As the silkworm builds the cocoon from the outside to the inside, the outer layers are more porous than the inner layers and have less sericin bonds [6,23], as shown in Figure 6. The sericin bonds connecting the fibers together within the layers are much stronger than the bonds connecting the layers together, the weaker bonds are the origin of the three-dimensional nonwoven Bombyx mori cocoon structure [6,7].

![Figure 6 – Morphology of cocoon layers. Scale bar: 100 μm. Adapted from [23].](image-url)
The mechanical properties of the cocoons can be considered independent of the direction. Under tensile loading, the failure process is as follows: the sericin fractures and the weaker interlayer sericin bonds break before the stronger inter-fiber bonds. The de-bonding starts in the outer layers because of higher porosity and the weaker sericin bonding, then propagates into the rupture of the fibers, and so forth until the rupture of the inner layers [23]. As the porosity decreases from outer to inner layers, the mechanical properties of the layers increases, and in addition the mechanical properties of the fibers also increases when getting closer to the inner layer [23].

The nonwoven composite structure of cocoons have also inspired models for other materials such as nonwoven materials such as paper of particulate composites such as concrete [22].

2.4 ARTIFICIAL STRUCTURES

Inspired by both the outstanding properties of silk and the high performance cocoon design, other artificial structures build by silkworms can be designed and constructed. For example, the Mediated Matter group from MIT media lab designed and created a silk pavilion constructed by 6500 silkworms spinning silk on silk thread scaffoldings fixed on polygonal panel frames by a Computerized Numerical Control machine, which were folded into a pavilion [24].

It also has been observed that in order to spin a cocoon silkworms need a vertical support of at least 21 mm, such as a pole for example, otherwise in a flat environment, it only creates a nonwoven two-dimensional patch or web structure, where the density of the web increases at the boundaries [24]. Figure 8 shows the results of the influence of the variation of a vertical spinning environment for the creation of a cocoon.
Figure 7 – Completed Silk Pavilion at MIT Media Lab. [24,25]

Figure 8 – Variation of silk structures with the increasing verticality of the silkworms’ spinning environment. (a) No vertical support, height of vertical support: 0mm. (b) Height: 6mm. (c) Height: 18mm. (d) Height: 21 mm. (e) Height: 27 mm. Adapted from [25].
3  **COMPUTATIONAL TOOLS AND METHODOLOGY**

This chapter describes the computational tools used and the methodology applied in order to have a better understanding of the behavior of silkworm silk web structure under wind load.

3.1  **COMPUTATIONAL TOOLS**

Computational tools are essential to investigate and predict the behavior of materials. Computational modeling and simulations can be used to study the behavior of materials across scales, from the nano scale, with the protein sequence for instance to the macro scale with the investigation of fibers or web structures [1]. The advantages of using computational tools are numerous, the main one applied in this thesis is the possibility to control with great precision the applied force, or the wind load, and measure precisely the deflection of the structure. Besides, this computational experiment can be repeated endlessly with the same initial sample. This is a great advantage compared to experiments which can be destructive. For example, the study of the web structure under wind load can only be repeated the number of samples available as the aim is to get the failure deflection which also means the destruction of the web. In particular, as the samples are made from silkworms spinning silk, the structure has a random fiber arrangement and its results will not be identical each time. In addition to these advantages, the mechanical properties can be manipulated and the same sample can be studied again [1].

On the other hand, experiments are also important because they describe the real material behavior unlike computational models which describe a prediction of the behavior. The experiments can verify the model’s accuracy [26].

For this study, the simulations were carried out on LAMMPS (Large-scale Atomic/Molecular Massively Parallel Simulator) molecular dynamic code [1,27]. Molecular dynamics is a computational method used to determine trajectories of particles by solving Newton’s law of motion: \( F = ma \) [1,26]. Using molecular dynamic, macro-scale deformation, such as the deflection
of the web under wind load, can be predicted by the trajectories of particles at the mesoscale or micro-scale [1,26].

The results were displayed on the molecular visualization program Visual Molecular Dynamics (VMD). This tool displays and analyses the molecules or particles and their trajectories. The bonds between particles and their position can be measured on VMD.

3.2 Methodology

The methodology of the study is divided into an experimental part which explains how the silkworm silk structure was created and the wind tunnel test of this structure and a simulation part describing the model derived and the computational simulation of the structure.

3.2.1 Experiment

3.2.1.1 Creation of the single layer silkworm silk web

Silkworms purchased through Mulberry Farms, were reared on a mulberry chow diet from the fourth into the fifth instar, which is the final stage of their growth. At this instar, silkworms start to spin silk, originally meant to build the cocoon.

Each single layer silkworm silk web structure was spun by one Bombyx mori silkworm for three days. To make this structure silkworms were positioned in a 3 inch (76.2 mm) diameter wood ring, under which was a Plexiglas plate so that the freshly spin silk sticks on the ring only. The ring is 6 mm thick and 4 mm high, which is a not high enough vertical support for the silkworm to build a cocoon, as it has to spin around itself. In this almost flat environment, the silkworm spun a single layer of silk covering the ring and outside. This experimental setting is shown on Figure 9. The final web structure is obtained by cutting the single layer silk patch along the outer perimeter of the ring. This final structure is shown on Figure 10. The fibers are linked together with sericin glue and the web is glued on the ring with sericin as well, creating a circular single layer silk web.
3.2.1.2 Experimental test

The single layer silkworm silk fiber webs were tested under an increasing wind load until failure of the structure. The tests were carried out in the 1 foot x 1 foot (30.48 cm x 30.48 cm) wind tunnel provided by the department of Aeronautics and Astronautics at MIT. The wind speed of the wind tunnel is measured in pressure units Torr, which are converted in wind speed in meter per second using the Zahms table. The samples were tested until failure or under the maximum wind speed of the tunnel, 40 m/s.

Originally the fixation of the web structure on the wood ring only relies on the natural sericin glue produced by the silkworms which is relatively weak. Thus, under high wind speeds, the whole layer of silk might be detached from the ring and not break as predicted. To make sure that the failure of the web under wind load is only caused by the failure the silk and the structure, the silk fibers were glued along the circumference of the ring with wood glue in order to enhance the attachment between fibers and the frame.
The web frame was attached with four Kevlar threads on a 1 foot x 1 foot wood frame which was clamped at the end of the wind tunnel. This way, the web can be considered as the only object in the wind tunnel, by ignoring the influence of the threads. The threads were attached so that the web frame was positioned at the center of the wind tunnel, as shown on Figure 11.

![Figure 11 - Experimental setting of the wind tunnel test.](image)

The deflections of the webs were measured by scaling pictures from a stable camera. The camera was positioned in the same plan as the web, and knowing the dimensions of the ring the deflections could be derived. The camera focused on the point of maximum deflection which is contained in the same focal plan as the web ring frame.
3.2.2 Simulation

3.2.2.1 Model

The behavior of the structure was analyzed with a discrete element method. The fibers were modeled as a line of mesoscopic particles connected with bonds. Using the principles of Newton’s law, the trajectories of the particle can be determined and thus the macroscopic deformation of the web as well [1,6]. To build the physical web, the silkworms spun silk by rotating their head randomly, creating a web structure of randomly arranged fibers. For this thesis, two models of this web were studied: a hypothetical straight fibers web and a wavy fibers web which illustrates more accurately the structure of the geometry of the real web. Both these geometries were generated with MATLAB, visualized on VMD and simulated on LAMMPS.

3.2.2.1.1 Straight fiber web

The straight fiber model considers all fibers inside the ring frame straight. This is a hypothetical model, because the silkworms spin silk randomly when building the web and do not spin straight fibers from one end to the other end of the frame. This model is also a reference model in order to compare the simulations and the experiment.
The straight fiber web model, represented in Figure 13, consists of 933 fibers arranged randomly inside of the circular frame. Each fiber starts from a point and ends at another point of the frame, randomly generated. The fibers were modeled as a line of mesoscopic beads or atoms linked together with springs. For each fiber, the beads are separated at the distance $r_0 = 500 \, \mu m$.

With these settings, a random fiber structure can be generated. However, as soon as the wind load is applied the fibers will go through each other, because the beads from one fiber do not prevent the other beads from another fiber to go pass them. To prevent the fibers to go through, the beads coming from different fibers are bonded together if the distance between them is shorter than $\frac{r_0}{2} = 250 \, \mu m$. The diameter of the fiber chosen is $D = 30 \, \mu m$, because the the fiber is composed of two core brins of diameter going from $6.8 \, \mu m$ to $16.7 \, \mu m$ [28]. Consequently, the beads have an equivalent spherical radius of $R = 4.386 \cdot 10^{-5} \, m$, which is determined with the relation between the volume of the fiber segment and the volume of the equivalent mesoscale bead.

\[
\text{Volume of fiber segment} = \text{Volume of bead}
\]

\[
V_{\text{bead}} = \pi r_0 \left( \frac{D}{2} \right)^2 = \frac{4}{3} \pi R^3 = 3.53 \cdot 10^{-13} \, \text{m}^3
\]

Each model is randomly generated, so are the geometries. The model used for the simulations is composed of 49388 atoms, 100819 bonds and 48574 angles.

Considering the thickness of $t=28 \, \mu m$ measured from the single layer web structure spun by silkworms and the diameter of the web $d_{\text{web}} = 76.2 \, \text{mm}$, the volume of the silk web $V_{\text{web}} = \pi t \left( \frac{d_{\text{web}}}{2} \right)^2 = 1.28 \cdot 10^{-7} \, \text{m}^3$, the number and volume of beads, the porosity is derived from:

\[
\varphi = \frac{\text{Volume of void}}{\text{Volume of web}} = \frac{\text{Volume of web} - \text{number of atoms} \times \text{Volume of atoms}}{\text{Volume of web}}
\]

\[
\varphi = 0.86
\]

This model’s porosity is higher than the literature’s [23], which is:

\[
\varphi = 1 - \frac{499}{1300} = 0.62
\]
With the nominal density of silkworm cocoon of 499 kg/m$^3$ and the density of silk fibers of 1300 kg/m$^3$ [23].

3.2.2.1.2 Wavy Fiber web

The wavy fiber web model captures better the wavy and random geometry of the real web, due to the random head rotation movements of silkworms when spinning silk. This model was obtained by creating waves out of the straight fibers from the previous model.

Instead of separating all the atoms at the same distance $r_0 = 500$ μm which also is the equilibrium distance, every five atoms, the distance between atoms were reduced to half the equilibrium distance for the next five atoms. In this model generated, the fibers are under compression and as a column under compression buckles, the fibers become wavy at equilibrium. Indeed, after relaxing the model, the bonds between atoms regain their original equilibrium distance by bending into waves. The model picture better the geometry and randomness of the web, especially as the waves shapes cannot be controlled. This model is represented on Figure 14.

![Figure 13 - Straight Fiber Model.](image)

(a) Geometry visualization. (b) Schematic representation of the beads and bonds.
3.2.2.2 Simulation experiment

3.2.2.2.1 Wind load experiment

The two models were analyzed with LAMMPS to get the maximum deflection of the webs under wind load with the discrete element method.

Before applying the wind on the webs, the structure is relaxed to equilibrium for the stability of the model and is the initial state of the structure. In the case of the wavy fiber web model, the relaxation enables the straight fibers to become wavy, because of the shorter distance between atoms.

The fibers were considered to follow a (a) linear elastic, a (b) yielding and a (c) post-yielding strain hardening plastic regimes, the stress $\sigma$ increases with the strain $\varepsilon$. According to [10], the axial force is:

$$ F(r) = -\frac{\partial \varphi}{\partial r} $$
$$\frac{\partial \varphi}{\partial r} = \left[ \exp \left( \frac{r - r_b}{r_b} \Xi \right) + 1 \right]^{-1} \begin{cases} k_1(r - r_0), & r < r_1 \\ H_\varphi(r), & r_1 \leq r < r_2 \\ R_2 + k_2(r - r_2), & r_2 \leq r \end{cases}$$

With spring stiffness:

$$k_1 = \frac{E_1 A_0}{r_0} \quad \text{and} \quad k_2 = \frac{E_2 A_0}{r_0}$$

With the equilibrium distance $r_0 = 500 \, \mu m$ and the cross section of the fibers $A_0$.

Applying the methodology from the mechanics of mussel threads [10] to silkworm silk threads, the parameters $r_1$ and $r_2$ are the extensions right before and after yielding, derived from the force-extension curve converted from the experimental stress-strain curve from [4]. $r_b$ and $\Xi$ are parameters from the Fermi-Dirac distribution. $R_1$ and $R_2$ are simply derived from the continuity at $r = r_1$ and $r = r_2$. $H_\varphi(r)$ is the Hermite interpolation function, which is describing the smoothness of the curve at yielding and can be derived with the previous parameters.

Both the straight and the wavy fiber webs were studied for different mechanical properties of silk fibers with forced reeling speed [4]. The values were adapted from [4] using the linear fitting method from [10] in the following table (Table 1) and graph (Figure 15):

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Reeling Speed</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>4 mm/s</td>
</tr>
<tr>
<td>Initial Modulus $E_1$ (GPa)</td>
<td>8.55</td>
</tr>
<tr>
<td>Yielding Modulus $E_2$ (GPa)</td>
<td>0.77</td>
</tr>
<tr>
<td>Critical Strain before yielding $\varepsilon_1$</td>
<td>0.01</td>
</tr>
<tr>
<td>Critical Strain after yielding $\varepsilon_2$</td>
<td>0.08</td>
</tr>
<tr>
<td>Rupture Strain $\varepsilon_b$</td>
<td>0.371</td>
</tr>
<tr>
<td>Force Continuity Conditions (GPa)</td>
<td>$R_1$</td>
</tr>
<tr>
<td></td>
<td>$R_2$</td>
</tr>
</tbody>
</table>

*Table 1 – Mechanical properties for different forced reeling speed fibers.*
Figure 15 – Stress-curve derived from [4] using the method from [10] of different silks.

With

\[ \varepsilon_i = \frac{r - r_i}{r_i} \]

The bending stiffness is defined by adding an angular spring between two adjacent springs [10] and is derived from

\[ K_B = \frac{E_1 l}{2r_0} = \frac{E_1 \pi d^4}{128r_0} \]

The harmonic angle potential or the bending energy of one angular spring [10] is given by:

\[ \varphi(\theta) = K_B(\theta - \pi)^2 \]

The wind load is modeled as a drag force derived from Stokes’ law and is applied on all the beads [10] except the beads at the circumference of the ring, which are fixed with no displacement during the wind simulation. The drag force is given by:

\[ f_{\text{drag}} = -(6\pi \mu R)v \]

With \( \mu = 18.6 \ \mu\text{Pa}\cdot\text{s} \) the fluid viscosity constant at room temperature, \( R=4.386\cdot10^{-5} \text{ m} \) the equivalent spherical radius of the bead and \( v \) the chosen wind speed.
3.2.2.2 Deflection measurements

To get the initial state, the system is relaxed to equilibrium and the total energy converges to a constant value.

After applying the wind load on the web or the drag force on the beads, the deflection of the web is measured by taking the value towards which the plot of the maximum deflection converges with time.

However, for some cases, this method is not applicable because filaments can break which lead to several beads flying down and an infinite deflection. Even with some filaments failure, the structure as a whole does not break because of the high redundancy of the system. This is shown on the visualization on VMD and on the plot of the variation of the reaction force at the ring boundary with time. Indeed, when the deflection is stable and the web has not failed, the reaction force converges to a constant value with time. To get the maximum deflection of the web, the z coordinate of the atom farthest from the boundaries is directly measured on VMD.

The failure wind speed is obtained when the deflection is infinite and the reaction force drops abruptly. The failure is also displayed on VMD.

At each simulation, one deflection is measured. By repeating the simulations with different wind speeds, a graph of the variation of the wind load with time is plotted.
4 EXPERIMENTAL SECTION

4.1 EXPERIMENT

4.1.1 Method

The silkworm silk fiber web is tested under an increasing wind load until failure or at 40 m/s the maximum wind speed provided by the wind tunnel. The difficulty of this experiment is the accuracy of the measures and its experimental set up.

Indeed, it is possible to have sag in the Kevlar threads as the web frame is hand-knotted to the wind tunnel frame. As soon as the wind speed increases the web frame deflects with wind and goes out of the frame plane. In particular, the web is unstable at lower wind speeds and after the failure of the web, because threads, fibers or cables, need to be tensioned to be stable. Consequently, the measures of the web deflection were recorded by scaling pictures focused on the maximum deflection, taken at every wind speed instead of measuring the deflection with laser or video. Measure accuracy also comes from the precision of setting the wind speed by rotating the switch manually and the precision of picture scaling.

![Figure 16 – Deflection measure example. Experiment 4. Wind speed: 38.3m/s.](image-url)
To calculate the drag force of the web, the fibers are considered as an infinite circular cylinder, as the length of the fiber (76.2 mm) is infinitely greater than the diameter of the fiber (10-30 μm). The Reynolds number of the fiber is:

\[ Re = \frac{\rho v d}{\mu} \]

With \( \rho \) the fluid density, in this case the air density, \( \mu \) the viscosity, \( v \) the speed and \( d \) the diameter of the cylinder of fiber. With the numerical values, \( Re<<1 \), with this low Reynolds number, the drag coefficient \( C_D \) is inversely proportional to the Reynolds number, and:

\[ C_D = \frac{\text{drag force}}{\frac{1}{2} \rho v^2 d} \]

As a results, the drag force is proportional to the wind speed. Likewise, as stress is proportional to the force, the stress is also proportional to the wind speed [29]. The wind speed versus deflection graph has the same shape as the stress-curve.

Four random silkworm silk web structures were tested under wind load in the wind tunnel.

4.1.2 Results

Figures 17, 18, 19, 20 show the graphs of the variation of the wind speed with the deflection of the web measured for the four experiments.

As predicted, in the four experiments, the maximum deflection of the web increases with wind speed. As the stress-strain curve of silkworm silk fibers, this nonwoven fiber web is composed of a linear elastic part and a plastic strain hardening part.

The characteristic values are summarized in the following table (Table 2):
<table>
<thead>
<tr>
<th>Experiment</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>Average</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>At yielding</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Deflection (mm)</td>
<td>3.64</td>
<td>1.2</td>
<td>1.7</td>
<td>2.7</td>
<td>2.3</td>
<td>0.9</td>
</tr>
<tr>
<td>Wind speed (m/s)</td>
<td>25.5</td>
<td>27.6</td>
<td>23.7</td>
<td>29.2</td>
<td>26.5</td>
<td>2.1</td>
</tr>
<tr>
<td>At failure</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Deflection (mm)</td>
<td>5.4</td>
<td>2.0</td>
<td>13.0</td>
<td>9.8</td>
<td>7.6</td>
<td>4.6</td>
</tr>
<tr>
<td>Wind speed (m/s)</td>
<td>30.6</td>
<td>38.5</td>
<td>39.5</td>
<td>38.3</td>
<td>36.7</td>
<td>3.6</td>
</tr>
</tbody>
</table>

Table 2 – Characteristic experimental values

Except for experiment 1, the webs from experiment 2, 3 and 4 fails at hurricane wind speed, according to Beaufort scale [30].

The results from the experiments have the same order of magnitude and seem realistic. Even though the experiments behave the same way, there is a large difference between experiments especially between the second experiment and the other three, the elastic region of experiment 2 is short, from a low wind speed of 3.6 m/s to a wind speed of 29.9 m/s the web only deflects 1 mm, from 0.2mm to 1.2mm at the respective wind speed, as shown of Figure 18.

![Wind Speed vs Deflection]

*Figure 17 – Experiment 1: Variation of wind speed with deflection
Figure 18 – Experiment 2: Variation of wind speed with deflection

Figure 19 – Experiment 3: Variation of wind speed with deflection
Out of the four experiments, the last two have similar shape (Figure 21) and characteristic values (Table 3), and can be compared further.
4.1.3 Discussion

The results from the four experiments indicate that the variation of the wind speed with deflection varies the same way as the same way the stress-strain curve of the fiber, with a linear elastic and plastic region until failure.

To get a more precise and regular results, a solution would be to reiterate the experiment more times. By tightening the supporting Kevlar threads, the deflection of the frame is prevented and by improving the camera setup, the results should be more accurate.

The divergence of the numerical results mainly comes from the randomness of the structure, as the webs were built by uncontrolled silkworms and only the frame supporting the web is fixed and regulated. Consequently, silkworms can create webs with variable density from web to web or even within the web itself, as shown in Figure 22. This problem can be solved checking the density with SEM pictures and only compare deflection results from webs which have the same density.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>3</th>
<th>4</th>
<th>Difference</th>
<th>Average</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deflection (mm)</td>
<td>1.7</td>
<td>2.7</td>
<td>37.0%</td>
<td>2.2</td>
<td>0.5</td>
</tr>
<tr>
<td>Wind speed (m/s)</td>
<td>23.7</td>
<td>29.2</td>
<td>18.7%</td>
<td>26.5</td>
<td>2.8</td>
</tr>
<tr>
<td>Deflection (mm)</td>
<td>13</td>
<td>9.8</td>
<td>32.7%</td>
<td>11.4</td>
<td>1.6</td>
</tr>
<tr>
<td>Wind speed (m/s)</td>
<td>39.5</td>
<td>38.3</td>
<td>3.1%</td>
<td>38.9</td>
<td>0.6</td>
</tr>
</tbody>
</table>

Table 3 - Comparison between experiment 3 and 4

Figure 22 – Web samples used for wind tunnel experiments. (a) Experiment 1. (b) Experiment 2. (c) Experiment 3. (d) Experiment 4.
4.2 SIMULATION

4.2.1 Method

To complement the wind tunnel experiments, a straight fiber and a wavy fiber model were studied under wind load simulations. Both models were randomly generated. Instead of applying an increasing load until failure, for the simulations, a constant wind load was applied and the deflection was measured, this procedure is reiterated until the wind load which breaks the web structure is found.

The deflections were measured after the system has stabilized over time. The stable web state is identified when the z-coordinate of the farthest bead is converges to a constant value which corresponds to the maximum deflection (Figure 23). In the case of some fiber failures, beads detached from the fiber have an infinite z-coordinate (Figure 24(a)), the model is considered stable when the reaction force has stabilized to a constant value, which is also the higher tension force at the boundary of the web (Figure 24(b)). Before the localizing the stable state, the model is relaxed to equilibrium which is reached when the total energy becomes constant (Figure 25).

![Deflection vs Time](image)

*Figure 23 – Variation of the deflection with time. Wavy fiber model. Fiber reeling speed: 4mm/s. Wind speed: 29.9 m/s*
For each model, wind load simulations were carried out for fibers with different mechanical properties, but within one web, the properties of the fibers are identical. The chosen mechanical properties come from the different spinning silk of forced reeling, summarized in Table 1.
4.2.2 Straight fiber model

4.2.2.1 Results

As expected for each forced reeling speed fiber web, the deflection increases as the wind speed increases. As shown on Figure 5, as the reeling speed increases, the produced fiber is stiffer and less extensible. Just like the fibers, the webs made of these different fibers deflect less as the reeling speed increases, the webs with higher stiffness fibers are less extensible than the webs with lower young modulus, as shown on Table 4 and Figure 26.

<table>
<thead>
<tr>
<th>Reeling speed</th>
<th>4 mm/s</th>
<th>13 mm/s</th>
<th>20 mm/s</th>
<th>27 mm/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum deflection (mm)</td>
<td>13.4</td>
<td>11.8</td>
<td>9.2</td>
<td>8.3</td>
</tr>
<tr>
<td>Wind load at failure (m/s)</td>
<td>478.1</td>
<td>581.1</td>
<td>478.1</td>
<td>537.8</td>
</tr>
</tbody>
</table>

*Table 4 – Deflection and wind load at failure for different reeling speed. Straight fiber model.*

*Figure 26 - Variation of wind speed with deflection and spinning speed. Straight fiber model*
As predicted, the failure wind load of the stiffer material, or the material made of fast reeling fibers, is higher than the softer material, when comparing the web made of 13 mm/s reeling speed to 4 mm/s and the web of 27 mm/s to 20 mm/s. However, the webs made of the highest reeling speed (20 mm/s and 27 mm/s) fibers do not behave like expected because their failure wind load should be higher than the webs with lower reeling speed (4 mm/s and 13 mm/s) fibers.

4.2.2.2 Discussion

The results obtained from the simulations of the straight fiber model confirm one of the hypothesis: as the material or the fiber becomes stiffer and less extensible, the structure or the web fails at a smaller deflection.

The other theory stating that the webs with higher stiffness material should break at a higher wind load has not been confirmed. This phenomenon could be explained by the high randomness and thus the high redundancy of the web structure.

For instance, the fibers can be studied with a cable model, which only takes tension:

\[ F = ke = \frac{EA}{L}e \]

With F the axial force of the cable, e the elongation, k the stiffness which is constituted of E the Young modulus, A the cross sectional area and L the length of the cable. The cables are loaded uniformly. For simplification, let’s use the model of the cable simply supported with one vertical load at half-length which behaves qualitatively the same way as the cable under uniform load, as shown on Figure 27.
With this model:

\[ P = \frac{2F}{L} u \quad \text{with} \quad F = \frac{EA}{L} e \]

In the web all the fibers have the same properties, and the load applied on each bead is the same, therefore, only the length of the fiber or cable changes. The load \( P \) and axial force \( F \) are constant. According to the equations above, for \( E, A \) and \( F \) constant, the elongation \( e \) will be higher for shorter span cable than for longer span cables. Likewise, the vertical deflection \( u \) is smaller when the length of the cable is shorter, and greater when the cable is longer.

In this random nonwoven model, it is highly possible that shorter fibers are under longer fibers. For the same properties, the shorter fibers deflect less and can be considered as support for the longer cables. The wind load applied on the longer cables are transferred on the shorter cables as point loads, in addition to the wind load already applied to the shorter fibers. The stiffer shorter fibers support the longer fibers as primary beams support secondary beams in structural engineering, as shown on Figure 28.
As the shorter fibers not only carry the wind load but also the load transferred from the longer fibers they will reach their failure stress faster, hence the lower breaking wind load of the web made of higher reeling speed fibers (20 mm/s and 27 mm/s).

This theory could be verified by plotting the stress inside each fibers over time. The length of all the fibers need to be known. When the stress falls to zero, it means that the fiber broke. If the first fibers to break are the shorter ones, this hypothesis is verified.

4.2.3 Wavy fiber model

4.2.3.1 Results

As expected the deflection of the four different wavy fiber web models increases as the wind load increases. For the lower reeling speed, the webs behave as expected and have similar shapes, for a spinning speed of 13 mm/s, the web is composed of higher stiffness and less
extensible fibers, and has a higher wind load and a smaller deflection at failure, compared to the 4 mm/s spinning silk fiber web, shown in Figure 29 and Table 5.

![Wind Speed vs Deflection](image)

*Figure 29 - Variation of wind speed with deflection and spinning speed. Wavy fiber model*

<table>
<thead>
<tr>
<th>Reeling speed</th>
<th>4 mm/s</th>
<th>13 mm/s</th>
<th>20 mm/s</th>
<th>27 mm/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum deflection (mm)</td>
<td>26.3</td>
<td>25.7</td>
<td>25.7</td>
<td>26.3</td>
</tr>
<tr>
<td>Wind load at failure (m/s)</td>
<td>204.7</td>
<td>268.9</td>
<td>233.1</td>
<td>268.9</td>
</tr>
</tbody>
</table>

*Table 5 - Deflection and wind load at failure for different reeling speed. Straight fiber model*

However the web made of higher spinning speed 20 mm/s and 27 mm/s, have a greater deflection when comparing to the web reeled at 13 mm/s at any wind load, and their ultimate wind load is either equal or lower to the failure wind load of 13 mm/s spinning speed web. Comparing the web made of slow reeled fibers (4 mm/s), their deflections are greater for lower wind speed: until 90 m/s wind speed and 20 mm deflection for 20 mm/s reeled web and 150 m/s wind speed and 23 mm deflection for the 27 mm/s reeled web. For higher wind speed, the webs deflects more than the 4 mm/s web but still less than 13 mm/s web.

The results between the higher reeling speed fiber webs are also unexpected. The fast reeled 27 mm/s web deflect more than the 20 mm/s web until 210 m/s wind load with 24 mm
defection. The ultimate wind load of the web made of the stiffer material (27 mm/s spun fibers) is nonetheless higher than the web made of fibers with less stiffness (20 mm/s spun fibers), with 268.9 m/s and 233.1 m/s wind speed respectively.

Another observable result is the failure of fibers within the web which does not fail the whole web structure, as illustrated in Figure 30.

![Beads detached from the fibers](image)

*Figure 30 – Visualization of fiber failure with free detached beads. Wavy Fiber model. Reeling speed: 20 mm/s. Wind speed: 215 m/s.*

### 4.2.3.2 Discussion

The results obtained from the simulations of the wavy fiber model show that for low reeling speeds, the web is less extensible and stiffer with the less extensible and stiffer material. However, for the high reeling speeds, the web behaves unexpectedly to the material properties. They are more extensible than the low reeling speed webs for until a certain wind load.

Just as the straight fiber model, this unexpected behavior of the wavy fiber model could be justified with the higher randomness, because of the wavy fibers, and the high redundancy of the system. The lower breaking strength of the high speed reeling webs could be explained by the same mechanism as the straight fiber model. The shorter fibers support the wind load and the loads transferred from the longer cables as well, they are likely to break faster and at a slower wind speed, as shown in Figure 28.
The previous explication can be completed to justify the higher extensibility of the high reeled web compared to the slow reeled web, for this more complex wavy structure. Likewise, it is highly probable that shorter fibers are under longer wavy fibers. The shorter fibers, because they carry the wind load and the load transferred from the longer fibers will break (Figure 30) before the longer fibers. After failure, the longer fibers will expand their entire length hidden in the waviness of the structure, hence the high extensibility of the structure.

With \( W \) : Wind load
\( R \): Reaction force of the shorter fiber to the longer fiber
\( u \): Maximum deflection of the longer fiber.

*Figure 31 - Simplified diagram of the web mechanism after failure of shorter fibers. Wavy fiber model.*
The higher extensibility of the 27 mm/s web compared to the 20 mm/s web could be justified by this mechanism, until a fixed wind load is reached, and after which the 20 mm/s web is more extensible than the 27 mm/s web. At wind loads greater than this fixed wind load, the longer wavy fibers have already extended and can be considered to carry loads independently, as the supporting shorter fibers already broke. The extensibility and the breaking load can be considered to depend mainly on the properties of the material and not the structure, thus the higher failure wind load and the lower extensibility of the 27 mm/s web compared to the 20 mm/s web.

This hypothesis can be verified by recording the stress in every fibers over time, just as the straight fibers model. The stress in the shorter fibers should increase faster and fall to zero at failure.

For both the straight and the wavy model, the mechanical properties of web structures with fast reeled fibers (20 mm/s and 27 mm/s) are less performant than the structure made of slow reeled fibers (4 mm/s and 13 mm/s). Indeed, the fast spun structures break at a lower wind speed and have a greater deflection even though they are made of higher strength fibers. The natural rate is 10 mm/s [14] which is between the slow reeling rates 4 mm/s and 13 mm/s. These results are suggesting that Nature does tune the properties of material to ensure specific functions. Alone, the fast spun fibers are stronger than the slow spun fibers, although as a structure, the slow reeled fibers or fibers spun at a natural rate can carry a higher strength.

4.3 COMPARISON

The wind tunnel experiments were carried out to verify or invalidate the results from the simulations, and to find which of the two types of models is the most in agreement with reality.

4.3.1 Results

Figure 32 shows the variation of the wind load with the deflection for the straight fiber model and the wavy fiber model for the wind simulation. As predicted the wavy web deflects more and has a lower breaking load than the straight fiber model for any silk reeling speed or silk
mechanical properties. The higher extensibility is showed in Figure 33, where the deflection of the wavy web is greater than the straight web for the same wind load applied.

Figure 34 shows the variation of the wind load with deflection between the wind tunnel experiments and the wind simulations for both the straight and wavy model.

![Wind Speed vs Deflection Graph]

*Figure 32 – Comparison of the variation of the wind load with deflection between the straight fiber model and the wavy fiber model.*
Figure 33 – Deflection shape under wind load. Wind speed: 140 m/s. Reeling speed: 4 mm/s.
(a) Straight Fiber Model. (b) Wavy Fiber Model.

Figure 34 - Comparison of the variation of the wind load with deflection between experiments and simulations

A main difference between the simulations and the experiments is their numerical values, as shown in Table 6. The differences between the breaking wind loads of the simulations and
experiments are extremely large: the failure wind loads for the straight and wavy model are respectively 12 times and 5 times larger than experiments’. As for the maximum deflection, the straight model deflects 0.7 mm less than the experiments compared to the wavy model which deflects twice as much as the experiments.

<table>
<thead>
<tr>
<th></th>
<th>Experiments (3 and 4)</th>
<th>Straight Fiber Web</th>
<th>Wavy Fiber Web</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Average</td>
<td>Average</td>
<td>Difference with experiments</td>
</tr>
<tr>
<td>Maximum deflection (mm)</td>
<td>11.4</td>
<td>10.7</td>
<td>6%</td>
</tr>
<tr>
<td>Wind load at failure (m/s)</td>
<td>38.9</td>
<td>518.8</td>
<td>1234%</td>
</tr>
</tbody>
</table>

*Table 6 – Averaged deflection and wind load at failure for the simulations and experiments*

4.3.2 Discussion

As expected, at any reeling speed, the wavy fiber web structure is more extensible than the straight fiber structure because of the fibers’ hidden length in the wavy structure. The wavy web has also a lower breaking wind load than the straight web.

The shape of the variation of the wind load with deflection is different between the simulations and the experiments. For the experiments, wind speed versus deflection is composed of a linear elastic and a plastic strain hardening region whereas the simulation curves are only composed of a strain hardening region. The differences of shape are due to the different procedures during the experiments and simulations. For the wind tunnel experiment, an increasing load was applied over time until failure. While, for the simulations, a fixed wind load was applied and the constant value toward which the deflection converges to is measured. By repeating this procedure, the variation of the wind load with deflection can be plotted. The simulations are actually a creep test, a fixed load is applied, and instead of studying the effect of time in the deflection, only the converging value is recorded. A way to have similar shape would be to apply an increasing load on the model, just as the experiment.
However, the simulations results for the straight fiber web follows the results of the experiments for low wind speeds until 27.5 m/s, especially between experiment 3 and the straight model reeled at 4 mm/s. At breaking wind load, the deflections from the experiments are closer to the deflection of the wavy fiber web at the same wind load, according to Figure 34.

Overall, the real deflections takes values between the deflections of the straight fiber and wavy fiber model. To improve the precision of the model, the waviness of the web need to be adapted to the actual web. In this case, the model need to be less wavy so that the web deflects less.

As for the failure wind loads, the large differences may be due to the difference in density between the actual web and the models. To solve this problem, the porosity of the actual web could be measured by SEM imaging, the model could be modified to fit the properties of the actual web. Besides, in this unnatural flat environment which is the ring frame supporting the web, silkworms might spin silk at unusual and different rates, in addition to the variation of spinning rate with head rotation movements [22,23]. A more accurate solution would be to record the silk spinning pattern and reeling speed during the fabrication of the web with a camera or a magnetometer testing by fixing a magnet on top of the head of the silkworm as it has been done by Mediated Matter group from MIT media lab [24], and replicate the same structure for the simulation.

In addition, the model’s silk connections could be improved. In the studied models, the bonds connecting the different fibers have the same properties of the main fibers, that way, they are used to prevent the fibers to go through each other. The bonds connecting the fibers are in reality sericin bonds and are weaker than the structural fibroin fibers, they should break faster [14]. Nevertheless, if only weaker sericin bonds are modeled, during the simulations, the bonds will indeed break before, but the fibers will consequently go through. The new bond modeled need to allow fiber sliding when broken, as observed during the wind tunnel experiments.
4.3.3 Outlook

Aside from copying the real random silkworm silk structure to get more accurate and precise results, closer to the actual web, by constructing an appropriate model, the opposite can also be considered. Instead of adapting the model to the actual web, a silk web could be built according to a model and simulation, the experimental test on the artificial web would be a validation of the model. In this way, new engineered silk structures could be developed, optimized and studied.

To prevent randomness originated from the uncontrollable silkworms, the silkworm has to be immobilized, just as [12], but instead of fixing the pole on which is taped the silkworm, a proposal solution would be to fix the silkworm on a 3D printer head so that the pattern and reeling speed are artificially controlled: the structure and the silk mechanical properties are fully controlled. This solution would be an opportunity to test structures designed and optimized by simulations and investigate deeper the relationship between material and structure.

This experiment could also be compared and complemented with a synthetic elastomeric web which would be 3D-printed, just as the study on the 3D-printed synthetic spider web to find the relation between structural optimization and material properties [31].
5 CONCLUSION

5.1 SUMMARY

In this research, a single layer silkworm silk web made of randomly arranged fibers was created with silkworms and tested under wind load. The webs were tested under an increasing wind load until failure and the web deflections were measured. To complement the experimental test, a straight fiber model and a wavy fiber model with the same geometrical constraints as the actual webs were simulated under wind load. The variation of the wind speed with the deflection of the web was plotted by measuring the deflection for each fixed speed applied on the model. For both models, the simulations were carried out on webs made of fibers with different mechanical properties originated from the different fiber reeling speeds: 4 mm/s, 13 mm/s, 20 mm/s and 27 mm/s.

From the experiments, the variation of the wind speed with the deflection of the web was plotted. The web behaves the same way as the stress-strain curve of the material: the web is composed of a linear elastic region and a strain hardening plastic region.

Aside from the expected results, which is the deflection increasing with wind load, the simulations show the webs made of a stiffer fiber reeled at an unnatural speed (20 mm/s and 27 mm/s) break at a lower wind load than the webs constituted of weaker fiber but reeled at natural rate (4 mm/s and 13 mm/s). This phenomenon could be explained by the faster breakage of the shorter fibers supporting the longer fibers. The simulations suggest that Nature does optimize and tune the mechanical properties of the fibers to ensure specific functions of the cocoon layer inspired silk web, such as resisting impact loading.

The divergence of results from the experimental tests and the simulations indicate that the models and simulation procedure need to optimized to be in better accordance to the actual web. The model should have the same porosity, the same fiber properties and same geometry as the web. A model considering the sericin connections and the sliding of the fibers after failure...
of these bonds would provide more accurate results. As for the simulation procedure, a similar increasing load should be applied instead of a fixed constant wind load.

5.2 OPPORTUNITIES FOR FUTURE RESEARCH

The artificial single cocoon layer silkworm silk web is a complex structure because of its high redundancy and randomness in the arrangement of the fibers. This thesis proposed a hypothesis suggesting that for webs made of fast reeled fibers or stiffer and less extensible fibers, the shorter fibers breaks before the longer fibers because they carry not only the wind load but also the loads transferred from the longer fibers. To validate or invalidate this hypothesis, an analysis of the stress in all the fibers according to their length could be carried out. An investigation on the resilient behavior defective webs could complement this research.

To deepen the understanding of the behavior of silk within the web structure, the construction process of the silk web could be recorded by either a camera or magnetometer and reproduced in a model more consistent to the actual web. The model could then be tested under an increasing wind load, just as the wind tunnel experiment.

Another approach to investigate the relationship between material and structure would be to control the construction of the web instead copying the web into a model. This would require complete control of the silk spinning process. The worm could be immobilized on a 3D printer head, in this way, the reeling speed is monitored so are the properties of the fibers. This experiment would be an opportunity to investigate the behavior of an artificial structure made of property-designed silkworm silk and study their relationship.

Finally, a bottom-up approach could be considered to investigate influence of the protein sequence at nanoscale on the mechanical properties of the fibers to the silkworm silk web structure at macro scale. Experimental test on sequence-modified synthetic silk would complement the simulations and modeling. This study could lead to a better understanding of silk across scales and the creation of bio-inspired material designed to be more performant, lighter and cheaper.
6 REFERENCES


