The influence of post-buckling damage on the tensile properties of single wood pulp fibers

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Acknowledgements

I would first like to thank my teacher and supervisor, Professor Artem Kulachenko, for his support and guidance throughout the larger part of my engineering education at KTH.

I would also like to thank, Mr. August Brandberg, for his great insights, collaboration and valuable guidance throughout my thesis.

Lastly, I would like to thank my wife, Ina Andreolli, for her unconditional love and support. Without you, this would not have been possible.
The rapid growth of plastic waste from food packaging around the world demands renewable substitutes, such as natural fibers and biocomposites. Wood fibers are natural fibers extracted from trees and are commonly used in packaging. In order for renewable alternatives to compete against plastics and other non-renewable materials, a better understanding of the mechanical properties of single fibers at the micro-scale are necessary. A great deal of previous research into the mechanical properties of single wood fibers has focused on their tensile behavior, however, little work has been published about their compressive behavior. It is difficult to measure the compressive strength of single fibers directly due to fiber buckling.

The purpose of this study is to investigate how post-buckling of single wood pulp fibers affects the mechanical properties of fibers in tension. Two alternative hypotheses were tested through experiments in The Odqvist Laboratory for Experimental Mechanics at KTH. The major part of the thesis process has been invested in developing components called grippers, and testing methods for the Single Fiber Testing System, in order to be able to perform the experiments. The existing grippers were tested and alternative grippers were developed, as well as an alternative testing method without grippers, called the Paper frame method (PFM). PFM was used in the final experimental work to test the hypotheses.

The main finding from this study is that there is not enough evidence to suggest that the tensile strength or tensile stiffness of single wood fibers are significantly reduced by post-buckling damage. This finding is mostly relevant in the research and development of fibrous material with larger distances between individual fibers, such as low-density fiber network materials. The main findings from the single fiber testing methods development were that the existing grippers cannot prevent fiber slippage. Furthermore, the alternative gripper 22A with its arc design generates higher grip force than previous grippers but lacks surface friction in the contact region in order to prevent fiber slippage. PFM has an experimental success rate of over 80 % for trained users and easy usage for the operator. The testing equipment Single Fiber Testing System displays several systematic errors occurring in the post-processing process of tests with cyclic loads.
Sammanfattning


Huvud slutsatsen från denna studie är att det inte finns tillräckligt med bevis för att stödja hypotesen att enskilda träfibrers draghållfasthet eller dragstyrhet reduceras av skada som uppstår efter knäckning. Detta resultat är mest relevant för forskning och utveckling av fibernetverks material med större avstånd mellan fibrerna, såsom fibermaterial med låg densitet. Huvud slutsatserna från utvecklingen av testmetoder var att de befintliga grepparmarna inte kunde förhindra fiberoglidan. Den alternativa grepparmen 22A med sin bågkonstruktion genererade högre greppkraft än tidigare grepparmar men saknar rätt beläggning i kontaktområdet för att förhindra glidning av fiber. PFM har en hög test framgångsgrad med över 80 % för erfarna användare och den är enkel att arbeta med. Testmaskinen Single Fiber Testing System visar flera systematiska fel som blir märkbar under dataanalys av tester med cykliska belastningar.


1 Introduction

Natural fibers are all around us, in the clothes we wear, in the books we read, in the paper we draw on, and in the packaging that protects our food. Natural fibers are used in an ever-increasing range of applications. Today, natural fibers are even used as reinforcements in high-performance applications such as sports, motor sports, and space industries.

The present environmental challenges consisting of global warming and rapid growth of pollution are destroying the earth’s scarce resources and diverse ecosystems. Every year, an estimated 5 to 12 million metric tons of plastic enters the oceans. Additionally, approximately 89% of the plastic waste found on the ocean floor is single-use items, such as plastic bags [1]. Plastics accumulate in oceans, seas and on beaches worldwide, due to their slow rate of decomposition. Plastic waste is also found in marine species, such as in birds, shellfish and fish, and therefore in the human food chain [2]. Hence, there is a growing demand for sustainable materials and products, in order for humanity to live within the planetary boundaries with no waste generation. Natural fibers and biocomposites can play a role in transforming our societies to use recyclable and renewable materials and to minimize waste and emissions throughout material and product life cycles.

For natural fibers and biocomposites to compete against plastics and other non-renewable materials, increased knowledge of the mechanical properties of single fibers at the microscale is necessary. In this report, the focus lies on natural fibers extracted from plants, in particular wood fibers. The understanding of the fundamental mechanisms controlling the failure of single wood fibers in compression will enable better control, and more freedom for the material development focused on compressive properties, such as gaining valuable insight into the compressive behavior of paperboard. This can result in improved or new types of packaging material that can be used instead of plastic packaging. A great deal of previous research into the mechanical properties of single wood fibers has focused on tensile strength [3], [4], [5]. However, little work has been published about the compressive strength of single fibers. The reason for this is that it is difficult to perform controlled testing. During a uniaxial compression test, the fiber tends to buckle or fold before any useful information about the compression strength can be captured. There is no agreement in the research community on how to measure and assess the true compressive behavior of natural wood fibers. Nonetheless, by
testing paper in compression, it has been shown that compressive strength is lower than the tensile strength, sometimes only 30% of the tensile strength [6].

Purpose statement

The purpose of this study is to investigate experimentally how the post-buckling of single wood pulp fibers affects the mechanical properties of fibers in tension at The Odqvist Laboratory for Experimental Mechanics, KTH.

Single fiber testing with three continuous load steps will be performed, where the first and last load step will be tensile loading, and the second load step will initiate post-buckling. The independent variable is the second load step that has a specific displacement to initiate different levels of post-buckling depending on the test. The dependent variables are the tensile strength and tensile stiffness of single wood fibers.

New insights into how post-buckling of single wood fibers affects the tensile strength and stiffness are foremost valuable in the research and development of fibrous material with larger distances between individual fibers, such as low-density fiber network materials.

Hypotheses

The first alternative hypothesis, $H_1$, can be stated as: post-buckling leads to a lower tensile strength of single fibers. The null hypothesis, $H_0$, is defined as: post-buckling has no effect on tensile strength of single fibers.

The second alternative hypothesis, $H_1^{(2)}$, can be stated as: post-buckling leads to a lower tensile stiffness of single fibers. The null hypothesis, $H_0^{(2)}$, is defined as: post-buckling has no effect on tensile stiffness of single fibers.
2 Background

This section describes the theory on which the report is based.

2.1 Natural fibers

A fiber can broadly be defined as an object with a length-to-width ratio greater than one. Natural fibers are extracted from the environment, from either plants, animals, or minerals. Plant fibers are used in a wide range of applications, such as packaging, everyday products, construction materials, vehicle components, medical devices, aircraft structures and spacecrafts. It is also common that natural fibers are combined with synthetic materials and methods, in order to achieve the required material performance for a specific application [7].

Natural fibers are processed by hand, simple tools, or by industrial processes, in order to become useful for a specific purpose. Synthetic fibers are made from materials found in nature, such as petrochemicals and carbon. However, the raw material is not fibrous in the original state and is not extracted directly from living organisms, thus synthetic fibers are not the same as natural fibers [7]. Vegetable natural fibers are found from various sources, such as wood, grass, and bast, as shown in Table (1).

<table>
<thead>
<tr>
<th>Seed</th>
<th>Bast</th>
<th>Wood</th>
<th>Stalk</th>
<th>Grass</th>
<th>Leaf</th>
<th>Fruit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cotton</td>
<td>Flax</td>
<td>Softwood</td>
<td>Wheat</td>
<td>Bambo</td>
<td>Pineapple</td>
<td>Coir</td>
</tr>
<tr>
<td>Kapok</td>
<td>Hemp</td>
<td>Hardwood</td>
<td>Oat</td>
<td>Bagasse</td>
<td>Abaca</td>
<td>-</td>
</tr>
<tr>
<td>Milkweed</td>
<td>Ramie</td>
<td>-</td>
<td>Rice</td>
<td>Esparto</td>
<td>Sisal</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 1: Vegetable natural fiber classification. Modified from [7, p. 3].

Natural fibers which originate from plants share that their fundamental organic structural component is cellulose. Most plant fibers contain in addition to cellulose, the organic structural polymers hemicellulose, and lignin to a varying degree and composition [7]. The geometrical dimensions of some natural fibers are presented in Table (2). Wood fibers tend to have a similar width as human hair, around 20 µm.
Table 2: The geometrical dimensions of common natural fibers. Modified from [6, p. 238].

<table>
<thead>
<tr>
<th>Fiber</th>
<th>Width (µm)</th>
<th>Length (mm)</th>
<th>Length-to-width ratio (-)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wood</td>
<td>20-30</td>
<td>1-4</td>
<td>33-150</td>
</tr>
<tr>
<td>Flax</td>
<td>11-20</td>
<td>10-30</td>
<td>900-1500</td>
</tr>
<tr>
<td>Hemp</td>
<td>16-50</td>
<td>12-25</td>
<td>500-700</td>
</tr>
<tr>
<td>Cotton</td>
<td>15-30</td>
<td>25-60</td>
<td>1700-2000</td>
</tr>
</tbody>
</table>

The mechanical properties of natural fibers vary greatly between fiber sources, as well as between fibers of the same kind. Additionally, the mechanical behavior depends on if the fibers are in a dry or a wet state. Dry fibers commonly have higher stiffness and tensile strength than wet fibers, while wet fibers have higher breaking strain. Young’s modulus, tensile strength, and breaking strain of some natural fibers in the dry state are presented in Table (3).

Table 3: Young’s modulus, tensile strength, and breaking strain of some plant fibers in a dry state. Modified from [6, p. 239].

<table>
<thead>
<tr>
<th>Fiber</th>
<th>Young’s modulus $E$ (GPa)</th>
<th>Tensile strength $\sigma$ (MPa)</th>
<th>Breaking strain (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wood</td>
<td>35</td>
<td>120</td>
<td>-</td>
</tr>
<tr>
<td>Flax</td>
<td>80-110</td>
<td>840</td>
<td>1.8</td>
</tr>
<tr>
<td>Hemp</td>
<td>70</td>
<td>920</td>
<td>1.7</td>
</tr>
<tr>
<td>Ramie</td>
<td>80</td>
<td>900</td>
<td>2.3</td>
</tr>
</tbody>
</table>

2.2 Wood fibers

Wood fibers are extracted from hardwood and softwood trees. In temperate zones, hardwood trees are deciduous, which means that they seasonally shed their leaves. Hardwood trees are characterized by their broad leaves and that their seeds are carried in fruits, or nuts. In contrast to hardwood trees, such as oak, ash, and aspen; softwood trees are coniferous, and bear their seeds freely, not covered in any fruit or nut. Most softwoods are evergreen, such as pine and spruce [7]. In the context of composites, softwoods tend to be more appropriate since they are composed of long wood fibers, called tracheid [6].

A wood fiber can be idealized as a hollow tube, where the space at the center is called lumen. The fiber cell wall consists of four layers: the primary wall P and the three secondary layers, S1, S2, and S3. All the layers consist of reinforcing cellulosic microfibrils integrated into a matrix of hemicellulose and lignin. The thickest layer among northern softwoods is S2, which can occupy around 85 %
of the total fiber wall volume. The microfibrils in the S2 layer wrap around the fiber axis to form a spiral. The angle of the spiral with respect to the fiber axis is defined as the microfibril angle (MFA), see Figure (1) [6] [8].

![Figure 1: A schematic representation of natural wood fiber, redrawn from [9]. The fiber cell wall consists of four layers: the primary wall P, the three secondary layers, S1, S2, and S3. The MFA, $\phi$, of the S2 layer is defined in the way indicated.](image)

The MFA varies between fibers but is approximately constant within a single fiber. Small microfibril angles result in axially stiffer and stronger fibers; the S2 layers normally have a MFA between $10^{\circ}$ to $30^{\circ}$ [6]. The S2 layer determines the mechanical properties of the fiber since it influences the stiffness, strength and elongation potential of the fiber [8].

### 2.3 Single fiber behavior

Single wood fibers are irregular and anisotropic. Wood fibers are much stiffer in their length direction than in the transverse directions. The mechanical properties of single wood fibers show both elastic and viscoelastic characteristics. Additionally, wood fibers often contain defects, such as pits, wrinkles, and nodes. It is, therefore, no surprise that single wood fibers behave differently in tension and compression, and they change behavior over time [5][6]. Furthermore, moisture and temperature affect wood fibers significantly, especially moisture.
2.4 Experiments

In this section, the theoretical background for the tests is described.

**Tensile test**

The strain of the fiber can be described by:

\[ \varepsilon = \frac{\delta}{L} , \]  

(1)

where \( \delta \) is the true displacement of the fiber and \( L \) is the initial length of the fiber, also called free span [10]. If \( \delta \) is measured via cross-head movement, the true elongation of the fiber is a summation of the following quantities:

\[ \delta = \delta_r + \delta_s , \]

(2)

where \( \delta_r \) is the raw displacement, which is the motor position of the right manipulator and \( \delta_s \) is the slippage displacement of the left manipulator or sensor position. The testing machine is constructed in such a way that the positive motor position is along the x-axis and the positive sensor position is along the negative x-axis. In tension, the fiber is displaced in the positive x-axis, and the slippage occurs also in the positive x-axis direction, resulting in negative values. When summed together, the raw displacement data points will be positive whereas, the slippage displacement will be negative due to how the machine is constructed. This is important to consider in the post-processing part in order to compute the true displacement occurring during the experiments.

The average normal stress in the fiber can be estimated by [10]:

\[ \sigma = \frac{F}{A} , \]

(3)

where \( F \) is the applied force and \( A \) is the cross-sectional area of the fiber. The tensile stiffness can be described in the form of Young’s modulus with units GPa. The Young’s modulus can be computed by the following relation, if the stiffness, \( k \), in units N/m is known:

\[ E = k \frac{L}{A} , \]

(4)

where \( L \) is the free span of the single fiber between clamping points. The relation is based on Hooke’s law in one dimension.
During a tensile test, misalignment of the fiber in the testing machine can lead to shear stress and finally break the fiber. The fibers should lie as straight as possible in the tensile direction. Perfect alignment occurs only if the fiber can align itself during tensile loading [11].

**Compression test**

The same relations as for the tensile test can be used in a compression test. The main difference is that the stress or strain will be represented by a minus sign. Short free spans are required during compression tests. For instance, the compression strength for paperboard is measured with the help of the Short Span Compression test, where the free span is set to 0.7 mm [12]. The free span should be similar to that or smaller when testing single fibers. The free span must be larger than the average cross-sectional area of individual fibers, which tend to be approximately 20-50 µm. Misalignment is crucial when it comes to compression tests. A slight misalignment or imperfection in the fiber geometry will initiate buckling, post-buckling, or folding. Hence, perfect alignment is difficult to achieve in compression tests.

**Hypothesis testing**

The hypothesis testing was performed using t-tests with the one-tailed p-value. The tests are based on the assumptions that random samples were used in the experiments to obtain the data. Additionally, the dependent variable should be approximately normally distributed. This is true if the parent population is normally distributed or if the sample size is reasonably large $n \geq 30$. In this study, for some tests, the sample size is $n < 30$ and the parent population is unknown, which means that a decision will be made about the normal condition based on the appearance of the sample data. Furthermore, the individual observations need to be independent, which means that no relationship exists between the observations.

**Two-sample t-test with unequal variance**

In a two-sample t-test based on the assumption of unequal variance, the $t$ statistic is calculated by [13]:

$$t = \frac{\overline{x}_1 - \overline{x}_2}{\sqrt{s_1^2/n_1 + s_2^2/n_2}},$$

where $\overline{x}_1$ is the average of Sample 1, $\overline{x}_2$ is the average of Sample 2, $s_1$ is the sample standard deviation of Sample 1, $s_2$ is the sample standard deviation of Sample 2,
$n_1$ is the test sample size of Sample 1 and $n_2$ is the test sample size of Sample 2. The degree of freedom is computed by:

$$\begin{cases} 
    a = \frac{\left(\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2}\right)^2}{\frac{1}{n_1} - 1} \\
    b = \frac{(\frac{s_1^2}{n_1})^2}{n_1 - 1} \\
    c = \frac{(\frac{s_2^2}{n_2})^2}{n_2 - 1} 
\end{cases}$$

$$\nu = \frac{a}{b + c}.$$  

(6)

**Paired t-test**

In a paired t-test, the $t$ statistic is calculated by [13]:

$$t = \frac{\bar{d}}{s} \cdot \sqrt{n},$$

(7)

where $\bar{d}$ is the average of the difference between the before sample and after sample, $s$ is the sample deviation and $n$ is the test sample size. The degree of freedom can be computed by:

$$\nu = n - 1.$$  

(8)

In this case, $d = x_2 - x_1$ is the difference in stiffness before and after the post-buckling load step, where $x_2$ is the stiffness after the post-buckling load step and $x_1$ is the stiffness before the post-buckling load step. The average of the difference is defined as $\bar{d} = \bar{x}_2 - \bar{x}_1$.

### 2.5 Static friction force

The static frictional force $F$ in the contact region between fiber and gripper can be modeled as the following:

$$F = \mu N,$$

(9)

where $N$ is the grip force and $\mu$ is the coefficient of static friction.
The forces acting on the fiber in the contact region between the fiber and the gripper during tensile tests are shown in Figure (2). The approximate coefficient of friction for the steel against steel is $\mu = 0.74$ [14].

Figure 2: Forces acting on the fiber in the contact region between fiber and gripper.
3 Method

This section describes the development of single fiber testing methods for the Short Fiber Testing System in the Solid Mechanics Laboratory at KTH. Additionally, all the necessary equipment and methods used in order to perform the experiments are outlined. Finally, the hypothesis testing is presented.

3.1 Grippers

Simple methods to improve the friction of existing grippers, and the development of alternative grippers are described in this section.

Simple methods to improve existing grippers

At the beginning of the thesis, the grippers belonging to the Short Fiber Testing System that is used to perform the single fiber testing at KTH were not working properly. The grippers that hold the single fibers during a test, were not optimally designed. During a single fiber tensile test, the fiber tended to start to slip after a specific tensile force, or the grip force was too high, thus damaging the fiber directly when closing the grippers around the fiber. These issues prohibited the aim to determine the mechanical properties of the fiber. Before developing alternative grippers, methods to improve the friction between fiber and grippers were tested. All the existing grippers were based on a similar design, as can be seen in Figure (3). The model 6H was tested several times and previous Ph.D. students had used the other grippers without any experimental success.

![Model 6H](image)

Figure 3: Four of the existing grippers, none of which worked properly during tensile tests. Only the gripper model 6H was used in this study.
First, a method where small pieces of tape were placed on each end of the fiber was tested, see Figure (4). This method was not practical, since it was very tedious to apply the tape on the fiber ends. Additionally, it was very hard to pick up the specimen with the grippers from the pick-up platform. When testing this method, the fiber started to slip again. Despite having some adhesive on the gripper from the tape, the fiber slipped during tensile tests.

![Figure 4: Single wood fiber ends attached to pieces of tape.](image)

Secondly, a glue gun was used. Small portions of glue were applied onto the ends of the fiber, as shown in Figure (5). Thereafter, the dried glue dots were carefully cut into smaller portions so that the grippers could grip them. This method was easy and fast, and it gave proper friction between the glue and the grippers. However, it was very hard to control the placement in the grippers leading to large misalignments. It was also observed that the glue started to deform with the fiber, which made this method unworkable.

![Figure 5: Single wood fiber ends attached to glue from a glue gun.](image)
Finally, an approach with paper frames with narrow slits was tested. The fiber was taped onto the paper clip across the narrow slit, and extra tape with the sticky area against the grippers was applied on the already taped area, see Figure (6).

![Figure 6: Single fiber ends attached to a folded paper frame with tape.](image)

This approach was more practical from the aspect of gripping the fibers. However, during the tensile test, the fiber started to slip. Thus, the tape and tape adhesive were not enough to avoid fiber slippage. The conclusion from these simple testing methods was that since the fiber slippage occurred even with adhesive in the contact region between the fiber and gripper, there was a need to develop alternative grippers with increased friction.
Grippers with inserts

The manufacturer of the Short Fiber Testing System developed grippers with inserts made from elastomers, as presented in Figure (7). These grippers promised higher friction between fibers and grippers, as well as other advantages, such as the possibility to easily change the insert material.

![Figure 7: Gripper H1 with inserts from both top and side view.](image)

These grippers were tested as previous simple tests. The fiber slipped during the tensile test, both from the left and the right gripper. Furthermore, for some cases when the grippers closed, the insert material started to deform and move away from its original position. Additionally, there did not seem to be any practical possibility to change inserts without damaging the gripper itself since it is small and fragile. This suggests that it might be easier to manufacture the gripper in another material directly, such as Plexiglas. The advantage of these grippers was that they did not seem to cause any damage to the single wood fibers when closed.
The development of alternative grippers

Single fiber testing with the existing grippers all displayed fiber slippage. Slippage even occurred with gripper model 6H with applied adhesive on the contact region between fiber and gripper. This led to the conclusion that it was necessary to develop alternative grippers.

The aim of the development of alternative grippers was to create grippers that make it possible to grab and hold single fibers without slippage and without damaging the fibers during tests. The grippers should also be easy to use and last for a long time before being changed.

The main strategy to develop the alternative grippers was to focus on the frictional force in the contact region. To improve the frictional force, $F$, in the contact between the fiber and the gripper, is either to increase the grip force, $N$, and/or the frictional coefficient $\mu$, see Equation (9). The gripper model 6H was analyzed by simplifying it to mainly consist out of two lengths $a$ and $c$, as shown in Figure (8).

![Figure 8: Simplified model of the gripper model 6H.](image-url)
Optimization

Simple analytical models were constructed in order to guide the design process. The first analytical model is based on the assumptions of small deformations and that the horizontal force, $H_A$, is approximately equal to zero and lastly, small-angle approximation ($\phi \approx 0$, $\sin(\phi) = \cos(\phi) \approx 1$), see Figure (9).

![Figure 9: The first analytical model.](image)

The equilibrium equations are:

\[
\rightarrow: \quad H_B - N = 0 \\
\uparrow: \quad V_A + F = 0 \\
\hat{A}: \quad N(a - b) - F \cdot c + H_B \cdot b = 0.
\]  

(10)

Solving for the grip force, $N$, gives:

\[
N = \frac{c}{a} \cdot F, 
\]  

(11)

where $F$ is the load applied when moving the manipulators and should not be mistaken for the frictional force.
The second analytical model is based on the assumptions that the horizontal force, \( H_A \), is approximately equal to zero and that small-angle approximation is valid, as shown in Figure (10).

The equilibrium equations are in this case:

\[
\begin{align*}
\rightarrow : & \quad H_B - N = 0 \\
\uparrow : & \quad V_A + F = 0 \\
\hat{O} : & \quad N(a - v) - F(c + u) + F \cdot u = 0 .
\end{align*}
\]  

(12)

Solving for the grip force gives:

\[
N = \frac{c}{a - v} \cdot F .
\]  

(13)

The optimization concluded that to maximize the grip force, \( N \), the length \( a \) must be minimized, and the length \( c \) must be maximized, see Equation (11) and (13).
**Main design decisions**

The alternative grippers are based on the existing gripper model 6H. The main strategy for the alternative grippers is to improve friction by focusing on the grip force. The alternative grippers need to be able to generate a larger grip force than previous grippers to prevent fiber slippage. The optimization concluded that in order to maximize the grip force, and thus the frictional force, length $a$ must be minimized, and length $c$ must be maximized. Length $a$ is constrained and cannot be reduced much in comparison to length $c$, hence the focus will be on length $c$. All the main design decisions are presented in Figure (11).

![Diagram of main design decisions](image)

Figure 11: The main design decisions for the alternative grippers based on the existing gripper model 6H.

- **A**: Remove the top part so that the maximum grip force occurs close to where the fiber enters the grippers.
- **B-B’**: Align all components.
- **C-C’**: Increase the grip force, $N$, by increasing the distance, $c$. 


The first design decision, A, is to remove the top part of the gripper so that the maximum grip force occurs close to where the fiber enters the gripper contact region. The second change is to align all the gripper sections to line $B'-B'$ from line $B-B$. This will improve the user experience during experiments since it makes it easier to visually see how much the grippers are closed or open. The third design is to simply increase the length $c$, as suggested by the optimization, $C-C''$. This will improve the grip force. Additionally, by using an arc design instead of a triangular design, the grip force can be further improved, see Figure (12).

Figure 12: Arc structure improves the grip force.
The alternative gripper development led to two new grippers, gripper 22A och gripper 23A, presented in Figure (13). Since gripper 22A with its arc design promised higher grip force than gripper 23A, it was used extensively.

Figure 13: The development of alternative grippers resulted in gripper 22A and 23A.
Test of manufactured alternative grippers
The first manufactured version of gripper 22A can be observed in Figure (14). The grippers were produced with too low precision than required for such small components. This would be a great disadvantage since the aim was to prevent fiber slippage during tensile tests. Even though the gripper 22A displayed improved grip behavior during tensile tests in comparison with previous gripper models, the rough surface in the contact region resulted in fiber slippage and unpredictable behavior.

Figure 14: Gripper 22A manufactured with lower precision.

In an attempt to improve the surface qualities, common nail polish was applied in the contact region to smooth the surface, as shown in Figure (15).

Figure 15: Low precision manufactured Gripper 22A with applied nail polish in the contact region.

This resulted in improved testing behavior by preventing fiber slippage to a higher degree than before, however, at a specific tensile force the fiber started to slip.
Every time the fiber starts slipping, the grip was increased, and the fiber stopped slipping until the tensile force reached yet another critical level. The gripper 22A seemed to provide enough grip force but lacked the correct frictional surface quality. The applied nail polish did improve the surface but did not provide enough friction.

As the next effort to improve the friction, the double-sided tape was applied in the contact region, see Figure (16). This was impractical in many ways since it was hard to grip and control the fiber due to the adhesive. No proper tensile test could be performed with this approach.

![Figure 16: Low precision manufactured Gripper 22A with double-sided tape.](image)

The next approach mixed nail polish and fine sand, as shown in Figure (17). The fine sand was not fine enough. Fiber slippage still occurred and resulted in a more unpredictable behavior than solely with nail polish. It was tedious and challenging to distribute the fine sand evenly onto the gripper surfaces in the contact region.
Figure 17: Low precision manufactured gripper 22A with nail polish mixed with fine sand.

The gripper 22A was also manufactured with higher precision as observed in Figure (18) to the right. Even with higher precision, the fiber slipped during tensile tests similar to the case with the lower precision manufactured gripper 22A with nail polish. This suggested that the way forward would be to work with the coefficient of friction in order to reach sufficient friction between gripper and fiber.

Figure 18: Gripper 22A manufactured with lower precision to the left, and with higher precision to the right.
The gripper 23A was also tested, see Figure (19). It performed identical to the model 6H and seemed to lack grip force capabilities.

![Figure 19: Gripper 23A manufactured with lower precision.](image1)

The gripper 22A and 23A were modified to fit the purpose of another research group at KTH. It resulted in the grippers N1 and N2, which are shown in the Figure (20).

![Figure 20: Gripper N1 and N2.](image2)
The gripper N1 and N2 are both basically identical to gripper 22A and 23A, respectively. However, there is one distinct difference. The fiber-gripper contact region is constructed in another way. The research group used N1 with a slight modification by applying nail polish in the contact region. Drawings for the grippers can be found in Appendix (I). The technical drawings for the gripper 22A and gripper 23A can be read from the drawings for N1 and N2. Only the contact region differs between the models.
3.2 Paper frame method

The experimental concept to test single wood fibers in tension by using a clamping method that glues the single fiber to appropriate material and then mounts it to the testing machine is not a new discovery [4]. In this study, the single wood fiber is placed and glued onto a custom-made paper frame with a slot. The paper frame is thereafter mounted on the testing machine and fixed in place by tightening two screws on either manipulator. It is essential for experiments that the paper frame consists of two pieces that are solely connected by a single fiber.

This method did not work on the first attempt. The fiber broke every time the paper frame was installed onto the testing machine. The paper frame was made of a too thin paper with the grammage 45 g/m², see Figure (21).

![Figure 21](image)

Figure 21: The first development phase of the paper frame method. The use of a too thin paper resulted in fiber breakage during installation.

In the second attempt, a thicker paper with grammage 300 g/m² was used in order to improve the bending stiffness of the paper. The paper frame was made of unbleached recycled paper with a rough surface. The fiber was glued onto the paper frame with super glue. The fiber did not break anymore during the installation of the paper frame in the testing machine. Now the fiber broke instead when performing the last step in the installation process. The last step is to cut the paper frame so that solely the fiber connects the two pieces of paper frames, see Figure (22). In the cutting process, the thickness of the scissor blade pushed the two paper pieces away from each other, directly loading the fiber to its breaking point. For this case, all the single fibers broke during installation before any tensile test could begin. The problem was clearly the cutting of the paper frame. Some
different cuts and methods were tested, such as only needing to cut one of the sides or cutting a v-slot instead of a straight cut. However, none of the cuts helped.

Figure 22: The second development phase of the paper frame method. The last cutting step in the installation process led to fiber breakage.

In the third attempt, it was clear that the cutting process needed to be eliminated. This could be achieved, by using small but strong clamps, as shown in Figure (23). The clamps that fulfilled the functional requirements were bought from the Swedish retail company Clas Ohlson. They had a contact area of approximately 10 mm × 25 mm. The paper frame was now cut out in two pieces and held together in the right position by the clamps. The fiber was thereafter glued onto the paper frames and the paper frame with fiber was installed onto the testing machine without fiber breakage. Finally, the first successful single fiber tensile test could be achieved.

Figure 23: The third development phase of the paper frame method resulted in a successful approach.
The development work continued by further improving the design of the paper frames. The most useful design found is presented in Figure (24).

Figure 24: Development of paper frame models. The model F5 was the most useful and the model used in the experiments.

Smaller changes were made such as adding a scale and grid on the topside of the frames and some shape changes such that the fiber would be visible during the test in the top view. The paper frame model F5 was the most practical design. It consists of important features such as free span of 1 mm, scale and relevant annotations, black background to increase fiber visibility, markings for the clamps, and the most optimal design in relation to the testing machine components and usage.
Several paper frame specimens before installation are presented in Figure (25). One of the advantages of PFM is that several specimens can be prepared daily and then simply installed and tested, one by one.

Figure 25: Prepared specimens. In this picture, the paper frame model F4 is shown.

The overall work process is simple for the user to perform. The most difficult task is likely to glue the single fiber to the paper frame which requires steady hands and some practice. The PFM has shown a high test success rate of over 80% for a trained user. In Figure (26) a mounted PFM specimen to the Short Fiber Testing System is presented.

Figure 26: Specimen installed in the testing machine.
The recommended procedure for PFM testing

The general outline of the PFM preparation process is described in Figure (27).

1. Isolate fibers and place them on a piece of glass
2. Print, cut out the paper frames and drill holes
3. Mark pieces and cut out the middle section
4. Attach clamps and glue fibers onto paper frames
5. Installation of the specimen to the test machine
6. Ready for the test (Total $\approx 3$ h)

Figure 27: The paper frame method preparation process.

The detailed PFM procedure description is presented in Appendix (G). In general:
1. Isolate fibers - approximately 20 fibers (30-60 min)
2. Print, cut out the paper frames and drill holes ($\approx 30$ min)
3. Mark pieces and cut out middle section ($\approx 30$ min)
4. Attach clamps and glue fibers onto paper frames ($\approx 60$ min)
5. Installation of the specimen to the test machine (less than 3 min)
6. Ready for the test (Total $\approx 3$ h)
3.3 Experiments

In this section, the experimental work is described. All the tests were performed with the Short Fiber Testing System in a controlled environment with ambient conditions of 25 °C and 45 % relative humidity. Furthermore, for all tests, the fibers were deformed at a constant rate of 1 µm/s.

Materials

Spruce chemo-thermomechanical pulp (CTMP) with a length-weighted average fiber length of 0.65 mm and mean width of 15.9 µm was used in this study. CTMP showcase less mechanical damage in contrast to for instance mechanical wood pulp. See Appendix (F) for the full specification of the fibers. The fiber isolation process is described in more detail in Appendix (G).

Short Fiber Testing System

The Short Fiber Testing System is a device that is developed to measure short fibers at the micro-scale, see Figure (28). The test machine with its micro-robotic measurements system is complex and is mainly used to test pulp fibers but can be used to test other materials as well.

Figure 28: The Short Fiber Testing System in the Solid Mechanics Laboratory at KTH.
Calibration
Calibration of the Short Fiber Testing System was done before the tests and thus eliminated as a source of error. Additionally, there was also system slippage in form of a displacement of the left manipulator during tests. The testing machine records both the raw displacement and slippage displacement of the left manipulator. The true displacement can be computed as presented in Equation (2). It is critical to use the true displacement and not the raw displacement when calculating the mechanical properties of single fibers.

Leica microscope
A Leica microscope was used in order to estimate the average cross-sectional area of the single wood fibers, see Figure (29).

![Figure 29: Leica microscope in the Solid Mechanics Laboratory at KTH.](image)

Measurement of the average fiber cross-sectional area
The cross-sectional area of the fiber can be approximated as a hollow circular cross-section even though the cross-section varies along the length of the fiber and can consist of multiple shapes. The hollow region of the cross-sectional area is difficult to determine with a microscope, thus in this study, the cross-sectional area of the fiber will be estimated to be a solid cylinder. This will likely lead to an underestimation of the tensile stress; however, it is not crucial for the study. There exist more precise methods to determine the fiber cross-sectional area if that is desired for future studies. The average fiber cross-sectional area is based on five
measurements of the diameter along the fiber length, measured from pictures from the Leica microscope, see Figure (30). The area is computed by \( A_i = \pi \frac{d_i^2}{4} \), and the total average fiber cross-sectional area can be written as:

\[
A = \frac{1}{5} \sum_{i=1}^{5} A_i.
\]  

(14)

The measurements were carried out at normal room temperature but without knowing either the exact temperature or relative humidity. Additionally, the measurements were done several days after the single fiber test. The measurements of the average cross-sectional area were taken after fiber failure, which is not ideal since the fiber splits up at failure. For this reason, the five measurements were taken further away from the failure point along the fiber.

Figure 30: The average fiber cross-sectional area was estimated with five measurements along the fiber with the help of a Leica microscope.
**Tensile test**

In the Tensile test (T), single wood fibers are subjected to a controlled tension until fiber failure. Data collection includes fiber tensile force and deformation at failure. The tensile stiffness is recorded within the elastic region. The tensile strength is computed by using the tensile failure force and the average fiber cross-sectional area, according to Equation (3).

**Tension-Unloading test**

The Tension-Unloading (TU) test is based on the following loading scheme:

1. Apply tensile load in the elastic region, 20 $\mu$m
2. Unload fiber, -20 $\mu$m
3. Apply tensile load until tensile failure

Data collection includes fiber tensile force and deformation at failure. Additionally, the tensile stiffness is recorded at load step 1 and load step 3 within the elastic region.

**Tension-Compression test**

The Tension-Compression (TC) test is based on the following loading scheme:

1. Apply tensile load in the elastic region, 20 $\mu$m
2. Apply compression load, x $\mu$m
3. Apply tensile load until tensile failure

A compression load simply means that the free span is reduced. It does not suggest that the single fiber experiences axial compression loading. Depending on the test performed, the second load step differs -40 $\mu$m for TC1, -80 $\mu$m for TC2 and -160 $\mu$m for TC3. The load steps were manually changed during tests since no such functionality was integrated into the testing machine at the time. The time to change the load step is on average approximately three seconds. The data collection is identical to the Tension-Unloading test.
The concept of the Tension-Compression test is illustrated in Figure (31). At point A, the load step changes from the first to the second. At point B, the load step changes from the second to the last load step until tensile failure. Additionally, at point B, the maximum level of post-buckling occurs.

![Figure 31: The concept of the Tension-Compression test load scheme. The degree of post-buckling at B depends on the load scheme for the second load step. There are three types: -40 μm for TC1, -80 μm for TC2 and -160 μm for TC3.](image)

**Relaxation test**

The single wood fibers display viscoelastic behavior; hence a relaxation test was performed in order to investigate if the relaxation would affect the experimental work significantly. In this test, the single wood fibers were subjected to a controlled tension load until the fiber elastically elongated 20 μm. The displacement was thereafter kept constant for 5 minutes. Data collection includes the tensile force as a function of time.
Hypothesis testing

In this section, the two alternative hypotheses are defined. The hypotheses are then tested by the previously described tests.

Tensile strength

The alternative hypothesis, $H_1$, can be stated as: post-buckling leads to a lower tensile strength of single fibers. The null hypothesis, $H_0$, is defined as post-buckling has no effect on tensile strength of single fibers:

\[
H_0 : \quad \mu_1 - \mu_2 = 0 \\
H_1 : \quad \mu_1 - \mu_2 < 0 .
\] (15) (16)

Tensile stiffness

The alternative hypothesis, $H_1^{(2)}$, can be stated as: post-buckling leads to a lower tensile stiffness of single fibers. The null hypothesis, $H_0^{(2)}$, is defined as post-buckling has no effect on tensile stiffness of single fibers:

\[
H_0^{(2)} : \quad \mu_2 - \mu_1 = 0 \\
H_1^{(2)} : \quad \mu_2 - \mu_1 < 0 .
\] (17) (18)
4 Result

In this section, the results from the development of single fiber testing methods for the Short Fiber Testing System are described. Furthermore, the results from experimental work are presented.

4.1 Grippers

The results from the development of alternative grippers are outlined in this section. In Figures (32) and (33), the effective von Mises stress in the gripper 22A is shown. The grippers close and open because of the two side sections of the gripper moves up or down, while the center section stands still. In the simulations for gripper 22A, the side sections were displaced ±0.4 mm. It can be observed that maximum von Mises stress reaches 200 MPa, and 240 MPa. This is lower than the yield strength of the gripper material, which is 250 MPa. The gripper geometry is simplified for the simulation in order to reduce the computational time. The simplification has no effect on physics since the geometric parts that are excluded do not affect the closing and opening mechanism.

Figure 32: The effective von Mises stress distribution of the gripper 22A in the closed position.
Figure 33: The effective von Mises stress distribution of the gripper 22A in the open position.

In Figure (34) the gap between the closed grippers are shown. According to the simulation, the gripper closes first at the top and bottom. For all grippers, the aim was that the gripper should first close near the top of the contact region, where the maximum grip force occurs and the fiber enters the gripper.

Figure 34: The gap between the two contact regions for gripper 22A.
The effective von Mises stress in the gripper 23A is presented in Figures (35) and (36). In the simulations for gripper 23A, the sides were displaced ±0.26 mm. It can be observed that maximum von Mises stress reaches 206 MPa, and 213 MPa, which is lower than the yield strength of the material.

Figure 35: The effective von Mises stress distribution of the gripper 23A in the closed position.

Figure 36: The effective von Mises stress distribution of the gripper 23A in the open position.
The gap between the closed grippers is shown in Figure (37). According to the simulation, the gripper closes first at the top.

Figure 37: The gap between the two contact regions for gripper 23A.
Comparison between gripper 22A and PFM

Gripper 22A with its arc design did display an improved ability to grip the single fiber. It is visible in Figure (38) where the force-displacement curves from gripper 22A made with lower precision and added nail polish, as well as the paper frame method, are shown. Several plateaus are visible in the curves from the gripper 22A. These curves highlight slippage between the gripper and the fiber. When the fiber slippage occurs, the gripper is closed further by the operator, and the force-displacement graph continues to rise. This occurs several times until the fiber breaks. This response did not occur with the previous gripper models, such as the gripper 6H model.

![Graph showing force-displacement curves](image)

Figure 38: Tensile tests with gripper 22A manufactured with lower precision (0.25 mm thread) in comparison to paper frame method.
The test with the gripper 22A that was manufactured with higher precision is illustrated in Figure (39). What can be seen is that fiber slippage occurred several times during the test of the fiber. It seems like that the gripper 22A with higher precision performs similarly to the gripper 22A with lower precision and added nail polish.

Figure 39: Tensile tests with gripper 22A manufactured with higher precision (0.20 mm thread) in comparison to paper frame method.
Figures (40) and (41) show the results from the gripper 22A with lower precision and added nail polish. In most cases, the fiber broke close to the contact region between fiber and gripper. In one instance, the gripper broke in the free span as desired. However, for all the tests re-gripping efforts were necessary during the tests.

Figure 40: Test with the low precision manufactured gripper 22A with nail polish. Fiber breakage close to the contact region.

Figure 41: Test with the low precision manufactured gripper 22A with nail polish. Fiber breakage in the middle section.
4.2 Experiments

The following section presents the results from several experiments with the aim to test the hypotheses.

Tensile test

The response of 30 single wood fibers during tensile tests is presented in Figure (42). The force-displacement graph is not normalized with respect to the fiber cross-sectional area or the original fiber length. Single wood fibers have naturally different material properties, which can be seen in the graph. It can be observed that the tensile force in the fiber reaches maximally slightly below 400 mN and the applied displacement of the fiber extends close to 140 µm.

![Graph showing force as a function of displacement. The test consisted of 30 individual wood fibers.](image)

Figure 42: Tensile test showing force as a function of displacement. The test consisted of 30 individual wood fibers.
Most of the time the fiber broke close to the paper frame contact as shown in Figure (43). However, in general, there was no significant difference in the force-displacement response between fibers who broke in the middle span or close to the paper frame.

Figure 43: Fiber tensile failure close to the paper frame contact.

The fiber breakage occurred occasionally in the free span, as shown in Figure (44).

Figure 44: Fiber tensile failure in the free span. The left column of images is before the tensile test and the right column after failure.
Figure (45) shows microscope images of different fiber breakages. In a), c) and d) the fiber broke in the free span. In b) the fiber broke close to the contact to the paper frame. This is the more common fiber failure.

Figure 45: Microscope images of the fiber breakage after the failure.
The fiber is glued to the paper frames. The glue distributes itself along the paper frame edge, as shown in Figure (46).

Figure 46: Microscope overview of how the glue distributes over the paper frame.
Tension-Unloading test

Two out of thirteen valid TU tests are presented in Figures (47) and (48). All of the graphs from the tests are shown in Appendix (B).

Figure 47: TU, first out of thirteen.

Figure 48: TU, second out of thirteen.
**Tension-Compression test**

The different load steps during the TC3 test are shown in Figure (49). In the second load step the maximum level of post-buckling occurs and in the third load step fiber failure takes place.

Figure 49: Load steps in the Tension-Compression tests, load scheme 3.
The maximum degree of post-buckling of the fiber in the different Tension-Compression tests is illustrated in Figure (50). It can be observed that the most developed fiber post-buckling happens in the TC3 test. It is common for the fiber to buckle more than one time and the buckling appears different for each test.

Figure 50: The maximum degree of post-buckling for the different Tension-Compression tests. Fiber post-buckling occurs for all the tests to a varying degree and shape.
Two out of sixteen valid TC1 tests are presented in Figures (51) and (52). All the TC1 graphs are shown in Appendix (C).

Figure 51: TC1, first out of sixteen.

Figure 52: TC1, second out of sixteen.
Two out of nine valid TC2 tests are presented in Figures (53) and (54). All of the TC2 graphs are shown in Appendix (D).

Figure 53: TC2, first out of nine.

Figure 54: TC2, second out of nine.
Two out of fourteen valid TC3 tests are presented in Figures (55) and (56). All of the TC3 graphs are shown in Appendix (E).

Figure 55: TC3, first out of fourteen.

Figure 56: TC3, second out of fourteen.
Comparison between tests

The tensile failure stress of single fibers from different tests is presented in Figure (57). The graph shows that the averages from each test align close to the average tensile failure stress at 260 MPa from the tensile test.

Figure 57: Comparison of tensile failure stress between tests.
The tensile stiffness of single fibers from different tests is presented in Figure (58). What stands out is that the average tensile stiffness from the various tests aligns reasonably well with the average stiffness of the tensile test taking the sample size of each test into consideration.

Figure 58: Comparison of tensile stiffness between tests.
Relaxation test

The five-minute relaxation test is presented in Figure (59). What can be clearly seen is that the viscoelastic behavior does not seem to be significant during the time scale of five minutes for the fibers tested.

Figure 59: Relaxation test for 5 minutes.
Hypothesis testing

The hypothesis testing concerning tensile strength is performed by a two-sample t-test based on the assumption of unequal variance, see Equation (5). The p-values and relevant information for each test are shown in Tables (4), (5), (6), and (7).

Table 4: Tension-Unloading test versus Tensile test.

<table>
<thead>
<tr>
<th></th>
<th>TU</th>
<th>T</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample mean</td>
<td>$\bar{x}_1 = 300$ MPa</td>
<td>$\bar{x}_2 = 260$ MPa</td>
</tr>
<tr>
<td>Sample standard deviation</td>
<td>$s_1 = 120$ MPa</td>
<td>$s_2 = 180$ MPa</td>
</tr>
<tr>
<td>Number of samples</td>
<td>$n_1 = 13$</td>
<td>$n_2 = 30$</td>
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<tr>
<td>Test statistic</td>
<td>0.81</td>
<td></td>
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<tr>
<td>Degrees of freedom</td>
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<td></td>
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<tr>
<td>p-value</td>
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</tbody>
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Table 5: Tension-Compression 1 test versus Tensile test.

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<th>TC1</th>
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<td>$\bar{x}_2 = 260$ MPa</td>
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<tr>
<td>Sample standard deviation</td>
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<td>$s_2 = 180$ MPa</td>
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<tr>
<td>Number of samples</td>
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<td>$n_2 = 30$</td>
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<tr>
<td>Test statistic</td>
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<tr>
<td>Degrees of freedom</td>
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<tr>
<td>p-value</td>
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Table 6: Tension-Compression 2 test versus Tensile test.

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<td>Sample standard deviation</td>
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<td>$s_2 = 180$ MPa</td>
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<td>Number of samples</td>
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<td>$n_2 = 30$</td>
</tr>
<tr>
<td>Test statistic</td>
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<tr>
<td>Degrees of freedom</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>p-value</td>
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<td></td>
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</table>
Table 7: Tension-Compression 3 test versus Tensile test.

<table>
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<th></th>
<th>TC3</th>
<th>T</th>
</tr>
</thead>
<tbody>
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<td>Sample mean</td>
<td>$\bar{x}_1 = 320$ MPa</td>
<td>$\bar{x}_2 = 260$ MPa</td>
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<td>Sample standard deviation</td>
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<td>$s_2 = 180$ MPa</td>
</tr>
<tr>
<td>Number of samples</td>
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<td>$n_2 = 30$</td>
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<td>Test statistic</td>
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<td>0.20</td>
</tr>
<tr>
<td>Degrees of freedom</td>
<td>23</td>
<td></td>
</tr>
<tr>
<td>p-value</td>
<td></td>
<td>0.20</td>
</tr>
</tbody>
</table>

The hypothesis testing concerning the change in tensile stiffness is performed by a two paired t-test, see Equation (7). The p-values and relevant information for each test are shown in Tables (8), (9) and (10). Furthermore, in Appendix (A), the detailed data from each experiment is presented.

Table 8: Tension-Compression 1 test versus Tensile test.

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample mean</td>
<td>$d = 0.31$ kN/m</td>
</tr>
<tr>
<td>Sample standard deviation</td>
<td>$s = 0.84$ kN/m</td>
</tr>
<tr>
<td>Number of samples</td>
<td>$n = 16$</td>
</tr>
<tr>
<td>Test statistic</td>
<td>1.5</td>
</tr>
<tr>
<td>Degrees of freedom</td>
<td>15</td>
</tr>
<tr>
<td>p-value</td>
<td>0.92</td>
</tr>
</tbody>
</table>

Table 9: Tension-Compression 2 test versus Tensile test.

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
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</thead>
<tbody>
<tr>
<td>Sample mean</td>
<td>$d = 0.31$ kN/m</td>
</tr>
<tr>
<td>Sample standard deviation</td>
<td>$s = 1.0$ kN/m</td>
</tr>
<tr>
<td>Number of samples</td>
<td>$n = 9$</td>
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<tr>
<td>Test statistic</td>
<td>0.88</td>
</tr>
<tr>
<td>Degrees of freedom</td>
<td>9</td>
</tr>
<tr>
<td>p-value</td>
<td>0.80</td>
</tr>
</tbody>
</table>

Table 10: Tension-Compression 3 test versus Tensile test.

<p>| | |</p>
<table>
<thead>
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<th></th>
<th></th>
</tr>
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<tbody>
<tr>
<td>Sample mean</td>
<td>$d = 0.15$ kN/m</td>
</tr>
<tr>
<td>Sample standard deviation</td>
<td>$s = 0.69$ kN/m</td>
</tr>
<tr>
<td>Number of samples</td>
<td>$n = 14$</td>
</tr>
<tr>
<td>Test statistic</td>
<td>0.82</td>
</tr>
<tr>
<td>Degrees of freedom</td>
<td>13</td>
</tr>
<tr>
<td>p-value</td>
<td>0.79</td>
</tr>
</tbody>
</table>
4.3 Identified post-processing problems

The post-processing process failed most tests, as presented in Table (11). The column title "Valid" corresponds to the tests that were accepted by the post-processing rules, which were outlined in Appendix (H). The column title "Failed" relates to the tests that did not fulfill the post-processing rules. All the nonphysical errors occurred in the post-processing process for tests involving cyclic loading.

Table 11: Result of the post-processing evaluation of valid tests.

<table>
<thead>
<tr>
<th>Test</th>
<th>Failed</th>
<th>Valid</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>T</td>
<td>2</td>
<td>30</td>
<td>32</td>
</tr>
<tr>
<td>TU</td>
<td>14</td>
<td>13</td>
<td>27</td>
</tr>
<tr>
<td>TC1</td>
<td>20</td>
<td>16</td>
<td>36</td>
</tr>
<tr>
<td>TC2</td>
<td>28</td>
<td>9</td>
<td>37</td>
</tr>
<tr>
<td>TC3</td>
<td>26</td>
<td>14</td>
<td>40</td>
</tr>
</tbody>
</table>

All the identified post-processing errors are explained in Appendix (H).
5 Discussion

The following section discusses the results from the gripper development, the paper frame method, as well as the results from the experiments.

5.1 Grippers

Neither the manufactured gripper 22A with lower precision and added nail polish nor the gripper 22A with higher precision did succeed in preventing fiber slippage. However, gripper 22A did with its arc design display an improved capability to grip the single fiber. The comparison between the gripper 22A and the PFM, in Figures (38) and (39), illustrates that the response of the gripper 22A tests is similar to the ones from the PFM. What stands out is that the force-displacement curves from the gripper 22A tests display fiber slippage several times during one single test. This result can be interpreted in mainly three ways according to the static friction force model, see Equation (9). The first interpretation is that the grip force generated by the gripper 22A is sufficient, however, the frictional coefficient is still too low. The second interpretation is that the grip force is still too low. The last interpretation suggests that possibly both the grip force and frictional coefficient need to be improved.

In the case that the frictional coefficient needs to be improved. It could be done by either applying color with fine particles on the grip contact regions, such as varnish with integrated fine micro-small grains or spray with micro-small grains. The method to add micro-small grains is similar to the successful experimental apparatus Jayne implemented in 1959 [3], where they used abrasive paper in the contact region to prevent the fiber from sliding during tensile tests. Another technique to improve friction is to build the gripper in a different material, such as Plexiglas. However, this method requires redesigning of the gripper to fulfill functional requirements. In the case that the grip force needs to be further developed, it could be done by simply extending the distance $c$ further than seen in the design of gripper 22A. This is possible since there are no components next to the grippers in the Short Fiber Testing System that would constrain this option.

It is difficult to avoid stress concentrations in the clamping zone between the single fiber and grippers. Most fibers broke near the clamping zone rather than in the middle section of the fiber. In fact, only once did the fiber break in the free span with the gripper 22A, however after several times of increasing the grip. It is
possible that the gripper induces damage onto the fiber ends when it closes which reduces the fiber’s mechanical properties. However, published research by Jayne [3] that used gripper-like components to grab the single fiber, observed that around 50 % of the fibers that were tested broke close to one of the grippers. They assumed even though that the stress concentrations due to the clamping were so small that they could be neglected, and they did not influence the measurements. It is questionable how much the clamping affects the mechanical properties of single fibers but is without a doubt something to consider in the development work. The clamping force should be well considered, enough grip force so that the fiber does not slip, but at the same time prevent damage to the fiber. This is a complex task to achieve practically since all fibers are unique with their irregular geometry.

5.2 Paper frame method

The paper frame method displays many advantages, such as a high test success rate of over 80 % for a trained user and simple and fast installation of the specimen to the test machine. It is also favorable that the fibers tend to break in the free span even though it might not be visible with the Short Fiber Testing System. Additionally, it is useful that it is possible to store the specimens after tests for different post-processing operations, such as the estimation of average cross-sectional fiber area with a microscope. The disadvantages are mainly the preparation operations and time and misalignment of the fiber. The total preparation time for around 20 specimens was around 3 hours. The preparation time can be significantly minimized by using a laser cutter in the cutting operations and by finding a more efficient fiber isolation technique. Some preparation steps are harder than others. Gluing the fibers onto the paper frames can be a difficult task since it requires steady hands and some practice. Using grippers does also take time and for a normal operator, it can be tedious and laborious work to pick up single fibers. It can be argued that using grippers tends to take a longer time than using the paper frame method, even though several extra procedures are required. It is possible that the method to use grippers can become a more efficient method in the future with for example in-built functionality that can pick, and grab fibers automatically and additionally minimize misalignment and damage. Misalignment can be reduced with the paper frame method by firstly glue the fiber as straight as possible over the gap between the paper frames parts. Thereafter, any misalignment can be adjusted manually by the operator when the specimen is fully installed in the testing machine.
As mentioned already in 1968 [4], it is important that the glue does not penetrate along the fiber length and in addition that the glue should not induce stress concentrations at the glue points. From a practical viewpoint, the glue should be easy to use, as well as drying in a reasonable time. The super glue fulfilled many of these requirements since it dried after a few minutes and was easy to handle. In this study, there was however no detailed tests performed to check either the glue penetration level or possible damage to the fiber from the glue. The 82 valid single fiber tests suggested that the stress concentrations are negligible since the tensile strength as well as stiffness corresponded to results from previous research and published literature [6] [8]. Furthermore, from the microscopic pictures, it can roughly be observed that the glue does not seem to penetrate any significant distance along the fiber, see Figures (30) and (45). It was also assumed that the glue was rigid in comparison to the fiber, thus not deforming significantly as the test was performed. In continued scientific work with the paper frame method, the fiber penetration level of the glue, as well as the mechanical properties of the glue should preferably be investigated. Additionally, any possible damage from the glue to the fiber should be considered.

Most fibers broke close to the fiber ends than in the middle of the free span as shown in Figure (43). There is no significant difference between tensile strength between fibers that break closer to the ends or in the free span. This suggests that the failure close to the glue points is due to the natural variability of the fiber or any kind of defects, and not due to the glue-fiber connection.

### 5.3 Experiments

The hypotheses were based on the idea that a reduction of the free span would lead to post-buckling with irregular buckled zones along the length of the fibers, as well as microscopic stress concentrations that could lead to damage or enhance existing damage of the fiber. Consequently, the post-buckling damage was assumed to affect the tensile properties of single fibers. From Tables (4), (5), (6), and (7) and additionally from Tables (8), (9), and (10), it can be observed that the p-value for each test is larger than 5 %. This means a failure to reject the null hypothesis at the significance level of 5 %. In other words, there is not enough evidence to suggest that the tensile strength or tensile stiffness of single wood fibers are reduced by post-buckling damage based on this study.
The fiber geometries show a large variety; thus, it is likely that the values of single fiber tensile strength and stiffness show large scatter. It is therefore important to perform enough tests in order to be able to capture the true mechanical properties. According to [4], around 100 to 200 measurements should be performed in order to estimate the average value of the fiber tensile stiffness. In this study, in total 82 valid tests were executed; however, every single test consists of in average approximately 16 valid tests. It can be argued that not enough tests were performed in this study. Due to difficulties with the testing machine, especially the in-built software that was not fully built for cyclic loading applications, in 4 out of 5 test types, over 50 % of the measurements made failed. For example, in the Tension-Compression 1 test, 20 out of 36 measurements failed in the post-processing evaluation due to systematic errors which seem to stem directly from the software. Only the tensile test showed reasonable results, where 2 out of 32 measurements failed. The reason for this can be that the tensile test does not perform any cyclic loading.

During the second load step in the Tension-Compression tests, the free span of the single fiber is reduced. This leads to buckling and folding of the fiber. The loading of the fiber is complex since the fiber geometry is irregular and the applied glue on the fiber is as well. It could be argued that the single fiber actually experiences bending more than axial compression in the second load case. For continued work where the compressive fiber properties are of interest, improved testing types for loading the fiber in axial compression need to be developed.

According to published research, the tensile strength of single wood pulp fibers ranges between 100-1500 MPa [5][6]. Furthermore, the tensile stiffness range between 10-80 GPa [15]. From Figure (57), it can be observed that in this study the tensile strength range between 50-1000 MPa with an average value of approximately 300 MPa. Moreover, in Figure (58) it is visible that the tensile stiffness varies between 2-9 kN/m with an average of approximately 4 kN/m. The stiffness can be described in units of GPa by implementing Equation (4), and assuming the free span, $L = 1$ mm, and the average fiber cross-sectional area, $A = 20 \, \mu\text{m}$. This results in tensile stiffness with range of 6-30 GPa. Hence, the tensile strength and stiffness of the single fibers in this study seem reasonable in comparison to established research.
The results from this study are most relevant for low-density fiber network material, such as foam-formed fiber networks [16]. The reasons for this is that the free span is larger than the free span of fibers in closely packed fiber network materials, such as paper sheets. The data suggest that post-buckling of single wood pulp fibers do not reduce their tensile strength and tensile stiffness. In other words, even though there are well-developed buckles or folds along the fiber at the maximum level of post-buckling, it will not damage the fiber so that the tensile properties are reduced.
6 Conclusion

In this section, the main findings of the analysis from the gripper development, paper frame method and experiments are described, as well as the identified post-processing problems.

6.1 Grippers

- The gripper 22A manufactured with lower precision and with added nail polish, as well as the gripper 22A manufactured with higher precision generates higher grip force than previous gripper models, but fails to fully prevent fiber slippage.
- Increased surface friction is required to prevent fiber slippage with gripper 22A. It is suggested to apply color with fine particles on the grip contact regions, such as varnish with integrated fine micro-small grains or spray with micro-small grains. Another option is to manufacture the gripper 22A in different materials, such as Plexiglas. In that case, the gripper design would need to be slightly modified to satisfy functional requirements.
- The grip force of gripper 22A can be further improved by increasing the length $c$, see Figure (8).
- Gripper 23 cannot prevent fiber slippage, as gripper model 6H.
- The pick-up process of single fibers with the grippers, as well as the minimization of misalignment can potentially be automated in the future.

6.2 Paper frame method

- The paper frame method has many advantages, such as a high test success rate of over 80% for a trained user and simple and fast installation. It is also practical for post-processing operations, such as microscope work.
- The influence of the glue on the fiber seems to be negligible in this study. However, in continued scientific work with the paper frame method, it is recommended to investigate how far the glue penetrates along the fiber length and investigate the mechanical properties of the glue. Furthermore, any possible damage from the glue to the fiber should be considered.
- The PFM preparation time for around 20 specimens by a trained user takes approximately 3 hours. The preparation time can be drastically reduced by improving the efficiency to isolate single fibers, and by automating the cutting process of paper frames with for instance a laser cutter.
• The PFM preparation operations that are the most difficult: are to isolate single fibers with fine tweezers and to glue the fibers onto the paper frames. These operations require steady hands, patience, and practice.
• It is possible to reduce fiber misalignment after installation by moving the manipulators. This could be automated in continued work.

6.3 Experiments

• There is not enough evidence to suggest that the tensile strength or tensile stiffness of single wood pulp fibers are reduced by post-buckling damage based on this study. In other words, even though there are well-developed buckles or folds along the fiber at the maximum level of post-buckling, it will not damage the fiber so that the tensile properties are reduced.
• The values of tensile strength, as well as tensile stiffness from the experiments, are reasonable in comparison to existing research.
• The results from this study are most relevant for low-density fiber network material, such as foam-formed fiber networks.
• It is not certain that enough tests were performed in this study.

6.4 Identified post-processing problems

• The identified post-processing problems stem from the Short Fiber Testing System directly in the form of systematic errors. They only occur in tests with cyclic loading and they occur mainly as nonphysical displacements in the force-displacement graph, see Appendix (H).
• Approximately 50% of the valid tests failed in the post-processing evaluation, see Table (11).
References


Appendix

A Experimental results

Table 12: Tension-Unloading test, TU. Stiffness at load case (1) and (3).

<table>
<thead>
<tr>
<th>Fiber</th>
<th>Stiffness (1) [kN/m]</th>
<th>Stiffness (3) [kN/m]</th>
<th>Difference [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3.86</td>
<td>5.42</td>
<td>+40.4</td>
</tr>
<tr>
<td>2</td>
<td>3.19</td>
<td>3.98</td>
<td>+24.9</td>
</tr>
<tr>
<td>3</td>
<td>4.47</td>
<td>5.99</td>
<td>+34.1</td>
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<td>4</td>
<td>2.25</td>
<td>3.23</td>
<td>+43.4</td>
</tr>
<tr>
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<td>4.43</td>
<td>4.97</td>
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<tr>
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<td>4.87</td>
<td>5.80</td>
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<td>5.89</td>
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<tr>
<td>13</td>
<td>5.23</td>
<td>6.40</td>
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</table>

Table 13: Tension-Compression 1 test, TC1. Stiffness at load case (1) and (3).

<table>
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<tr>
<th>Fiber</th>
<th>Stiffness (1) [kN/m]</th>
<th>Stiffness (3) [kN/m]</th>
<th>Difference [%]</th>
</tr>
</thead>
<tbody>
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<td>3.45</td>
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<td>16</td>
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</table>
Table 14: Tension-Compression 2 test, TC2. Stiffness at load case (1) and (3).

<table>
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<th>Fiber</th>
<th>Stiffness (1) [kN/m]</th>
<th>Stiffness (3) [kN/m]</th>
<th>Difference [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3.15</td>
<td>2.95</td>
<td>-6.51</td>
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<tr>
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<td>8.48</td>
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</table>

Table 15: Tension-Compression 3 test, TC3. Stiffness at load case (1) and (3).

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<th>Stiffness (1) [kN/m]</th>
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<th>Difference [%]</th>
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<tr>
<td>14</td>
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<td>4.76</td>
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</table>
B  Tension-Unloading test
C Tension-Compression 1 test
D Tension-Compression 2 test
E  Tension-Compression 3 test
## Fiber characteristics

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</tr>
<tr>
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<td>Width</td>
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<tr>
<td>Length</td>
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<td>Volume</td>
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<td>Length</td>
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### Arithmetic weighted (ISO)

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</thead>
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</tr>
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<td>15.9 µm</td>
<td>-0.1 µm</td>
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<tr>
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<td>0.0 %</td>
</tr>
<tr>
<td>Mean fibril area</td>
<td>62.1 %</td>
<td>-5.3 %</td>
</tr>
<tr>
<td>Mean fibril perimeter</td>
<td>26.0 %</td>
<td>0.4 %</td>
</tr>
<tr>
<td>Mean Fines</td>
<td>98.1 %</td>
<td></td>
</tr>
</tbody>
</table>

### Proportion

<table>
<thead>
<tr>
<th>Length (mm)</th>
<th>Proportion (‰)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-0.5</td>
<td>0.9</td>
</tr>
<tr>
<td>0.5-1.5</td>
<td>0.8</td>
</tr>
<tr>
<td>1.5-3</td>
<td>0.7</td>
</tr>
<tr>
<td>3-3.1</td>
<td>0.6</td>
</tr>
<tr>
<td>3.1-7.5</td>
<td>0.5</td>
</tr>
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</table>

### Accumulated Proportion

<table>
<thead>
<tr>
<th>Length (mm)</th>
<th>Accumulated Proportion (‰)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-0.5</td>
<td>0.001</td>
</tr>
<tr>
<td>0.5-1.5</td>
<td>0.009</td>
</tr>
<tr>
<td>1.5-3</td>
<td>0.017</td>
</tr>
<tr>
<td>3-3.1</td>
<td>0.024</td>
</tr>
<tr>
<td>3.1-7.5</td>
<td>0.030</td>
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</table>

### Length-Width

<table>
<thead>
<tr>
<th>Length (mm)</th>
<th>Width (µm)</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean length</td>
<td>0.649 mm</td>
<td></td>
</tr>
<tr>
<td>Mean width</td>
<td>0.257 mm</td>
<td></td>
</tr>
<tr>
<td>Mean shape</td>
<td>88.7 %</td>
<td></td>
</tr>
<tr>
<td>Mean fibril area</td>
<td>62.1 %</td>
<td></td>
</tr>
<tr>
<td>Mean fibril perimeter</td>
<td>26.0 %</td>
<td></td>
</tr>
<tr>
<td>Mean Fines</td>
<td>98.1 %</td>
<td></td>
</tr>
</tbody>
</table>

Date: 2015-03-20 12:40:26      Instrument number: 260

---

**Sample name:** 0 PFI_1  
**Sample type:** Mischung  
**Time:** 2015-03-20 11:28:20  
**Comment:**

**Number of fibers:** 7669 (412070)  
**Number of images:** 3970  
**Temperature:** 24.3 °C
Sample name: 0 PFI_1
Sample type: Mischung
Time: 2015-03-20 11:28:20

<table>
<thead>
<tr>
<th>Variable</th>
<th>Weighting</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>Length-Length</td>
<td>2,279 mm</td>
</tr>
<tr>
<td>Width</td>
<td>Length</td>
<td>26.5 µm</td>
</tr>
<tr>
<td>Width</td>
<td>Width</td>
<td>23.9 µm</td>
</tr>
<tr>
<td>Width</td>
<td>Area</td>
<td>37.9 µm</td>
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<tr>
<td>Width</td>
<td>Volume</td>
<td>42.6 µm</td>
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<td>Width</td>
<td>Arithmetic</td>
<td>15.9 µm</td>
</tr>
<tr>
<td>Width</td>
<td>Length-Length</td>
<td>40.7 µm</td>
</tr>
<tr>
<td>Shape</td>
<td>Length</td>
<td>86.2 %</td>
</tr>
<tr>
<td>Shape</td>
<td>Width</td>
<td>87.9 %</td>
</tr>
<tr>
<td>Shape</td>
<td>Area</td>
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</tr>
<tr>
<td>Shape</td>
<td>Volume</td>
<td>85.2 %</td>
</tr>
<tr>
<td>Shape</td>
<td>Arithmetic</td>
<td>88.7 %</td>
</tr>
<tr>
<td>Shape</td>
<td>Length-Length</td>
<td>84.3 %</td>
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<td>Fines</td>
<td>Length</td>
<td>60.1 %</td>
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<tr>
<td>Fines</td>
<td>Width</td>
<td>77.9 %</td>
</tr>
<tr>
<td>Fines</td>
<td>Area</td>
<td>17.0 %</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Variable</th>
<th>Weighting</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of fibers</td>
<td>Length-Length</td>
<td>7669 (412070)</td>
</tr>
<tr>
<td>Number of images</td>
<td></td>
<td>3970</td>
</tr>
<tr>
<td>Temperature</td>
<td></td>
<td>24.3 °C</td>
</tr>
<tr>
<td>Fines</td>
<td>Volumen</td>
<td>8.3 %</td>
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<tr>
<td>Fines</td>
<td>Arithmetik</td>
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</tr>
<tr>
<td>Fines Grenze</td>
<td>Length-Length</td>
<td>4.6 %</td>
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<tr>
<td>Number of fibers</td>
<td></td>
<td>7669 (412070)</td>
</tr>
<tr>
<td>Number of images</td>
<td></td>
<td>3970</td>
</tr>
<tr>
<td>Temperature</td>
<td></td>
<td>24.3 °C</td>
</tr>
<tr>
<td>Total fiber length</td>
<td></td>
<td>14963 mm</td>
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<tr>
<td>Total fiber surface</td>
<td></td>
<td>412,6 mm2</td>
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<tr>
<td>Total fiber volume</td>
<td></td>
<td>14,27 mm3</td>
</tr>
<tr>
<td>Length per image</td>
<td></td>
<td>4.0 mm</td>
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<tr>
<td>Number of fibers in sample</td>
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<td>978621</td>
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<tr>
<td>Mean kink angle</td>
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<td>50.0 °</td>
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<tr>
<td>Number of kinks per mm</td>
<td></td>
<td>0.432 mm-1</td>
</tr>
<tr>
<td>Number of large kinks per mm</td>
<td></td>
<td>0.111 mm-1</td>
</tr>
<tr>
<td>Number of kinks per fiber</td>
<td></td>
<td>0.521</td>
</tr>
<tr>
<td>Number of large kinks per fiber</td>
<td></td>
<td>0.133</td>
</tr>
</tbody>
</table>

Date: 2015-03-20 12:40:26      Instrument number: 260
G  Detailed PFM procedure description

The wood fibers are commonly stored in a container inside a refrigerator. The first step is to extract a small bundle of the fibers into another smaller container with a fine tweezer and then to add some water to dilute the mixture. The next step is to isolate the fibers from the diluted suspension by first pouring out a small portion of pulp fibers from the pulp container with a pipette onto a surface that can handle water, e.g., a black-colored cutting mat, see Figure (68).

Figure 68: Two fine tweezers and fiber suspension. The single fibers are picked out from the fiber suspension with the help of the tweezers and placed on a piece of glass.

Single fibers without any visible defects are selected and picked out from the fiber suspension with the help of two fine tweezers and a stationary binocular with magnification and an integrated light source. The handling of the fibers was carefully performed in order to avoid damaging the middle section of the fiber that is crucial for testing. It requires some practice before it becomes easier to isolate and handle the fibers since the fibers easily stick together into smaller bundles. Using two fine tweezers helps to isolate single fibers since one can hold a few fibers and the other tweezer can carefully grab single fibers from the other. It can take around one hour to find around 10 to 20 single fibers, depending on the skills and luck of the picker. There should exist other methods to isolate fibers that are more effective.
Let the single fibers then air dry freely on a piece of glass or appropriate material, see Figure (69). Prevent applying any tensile or compressive strains, since induced strains could impact the mechanical properties of the fibers.

![Figure 69: Single wood fibers laying on a piece of glass, ready for testing.](image)

The paper frame drawings are printed on unbleached paper with a rough surface and with a grammage between 220-300 g/m². The paper frames should optimally be laser cut since it saves a lot of time spent on manual paper cutting and drilling. If this option is not available, the following process is recommended. Start by drilling two holes (diameter 2 mm) with a screwdriver, where it is indicated according to the drawings. Thereafter, start cut out the single paper frames with a sharp scalpel. Number each frame, where it says Nr., additionally add test type, for example, write "T" for tensile test, and finally write down the date of the test on for instance the right side. It is important to annotate on both the top and bottom of the frame since in the next step, the paper frame will be cut into two pieces. When the middle section with a height of 1 mm is removed, it is time to attach the clamps and connect the two separate the paper frame again. It is important to test that the clamps have the appropriate clamping strength before using them. Some of the clamps are misaligned and do not have sufficient strength. This is easy to test by simply attaching them to the two paper frames and try to drag them off. If they begin to glide on the paper frame surface by a low drag force, it is probably best to use other clamps. The next step is to construct the paper frame specimen by attaching the two well-performing clamps. There should be an approximately 1 mm gap as designed and that the annotation lines from the top and bottom frames are as aligned as possible. The gap can be controlled with a ruler before the next step. This task requires some practice before the user become efficient.
The gluing process is the next step. Before applying the glue onto the paper frames, choose visually which fiber will be picked up from the piece of glass. Thereafter, with help of a magnifier, put a layer of glue on both sides of the paper frames close to the edge in the black-colored region. Rapidly, pick up the single fiber with a tweezer and place it on the paper frame. Place the fiber on the paper as aligned and straight as possible over the gap between the frame parts. The straighter the fiber lies across the gap; fewer misalignment adjustments are needed later in the testing process. If necessary, carefully distribute excess glue on the paper frame with some leftover paper tissue, so that it will dry faster. Be careful not to distribute the glue so that it reaches the drilled holes, this will complicate the installation process significantly. Let the glue air dry for a minimum of 15 minutes. The glue is a super glue from the German company STANGER. This super glue is suitable for gluing a wide range of materials and the setting time is relatively short.

The installation process starts by placing the specimen on the testing machine. The manipulators should be on the same height in the z-direction and be properly distant from each other in the x-direction and aligned in the y-direction. The distance between the holes should be 15 mm. The paper frame is installed by tightening two screws on either manipulator. Each screw has a corresponding metal plate that separates the head of the screw and the surface of the paper frame. This is important in order to avoid fiber breakage. When the paper frame is properly mounted to the manipulators, the clamps can carefully be removed. This is often the most critical step in the installation process since the fiber tends to break if the clamps are taken off with too much movement. Open the clamps slowly and with as controlled movements as possible, to avoid affecting the fiber.
The total installation process to the testing machine is shown in Figure (70).

Figure 70: The installation process of the PFM specimen to the Short Fiber Testing System.
H Identified post-processing problems

In this section, the guidelines used in order to sort out invalid tests are explained. The identified post-processing problems stem directly from the Short Fiber Testing System for the Tension-Unloading test and the Tension-Compression tests.

**Rule 1:** The tests should have a reasonable magnitude on the values of force and displacement for individual fibers. Skip graphs where maximum displacement or tension are unreasonable. Compare their values against other tests and existing research.

**Rule 2:** Skip graphs with clear vertical offsets, since it indicates something went wrong, see Figure (71).

Figure 71: Post-processing error displayed as a jump in the y-direction.
Rule 3: Skip graphs where the first stage of the first load cycle is clearly below maximum post-buckling level in the y-direction, since it indicates something went wrong, see Figure (72). The maximum post-buckling level is the region where the curve is below or close to zero along the y-axis, with negative displacement values on the x-axis. It displays itself often as a horizontal line.

Figure 72: Post-processing error due to that the first stage of the load cycle is lower than the maximum post-buckling level. This cannot be physically explained.

Rule 4: Data points during maximum post-buckling level must be lower than the zero level after the break. Skip graphs where the zero level is lower than the maximum post-buckling level in the y-direction.

Rule 5: Every graph from all tests is shifted along the y-axis. The graphs shift the distance between the zero level after breaking to the x-axis. If the zero level after fracture is below the x-axis, the graph is shifted in the positive direction. If the zero level after fracture is above the x-axis, the graph is shifted in the negative direction. After this vertical shift, the graphs are evaluated. If the maximum post-buckling level is above the x-axis after displacement, these graphs are skipped.
because it indicates something went wrong. There are several graphs, where the maximum post-buckling level is at the zero level, and sometimes have a few data points over the x-axis. These graphs are considered to still be valid since they can be interpreted as very close to zero.

**Rule 6:** All graphs are shifted horizontally so that it starts at the first data point that is considered as the starting point. The starting point is the beginning of the "stiffening region". The data point for the starting point is then shifted to the origin.

**Rule 7:** There are still some graphs that have been approved that have some small shifts vertically, or behave a little differently than expected, see Figures (73) and (74). They have been approved because these offsets seem slightly different from the ones mentioned earlier, and they seem more reasonable. There could be different micro mechanisms, which affect the fiber during the load cycles.

Figure 73: The first of two examples of valid tests which show some irregular force-displacement characteristics.
Figure 74: The second of two examples of valid tests which show some irregular force-displacement characteristics.

**Rule 8:** It is important that the data points which are important for the hypothesis look reasonable within the region in the graph. For example, the data points for determining the slope of the first load cycle should be in the elastic region of the force-displacement curve. There should not be a strange jump in the graph where the slope for the first load cycle or third load cycle occurs in the graph.
**Rule 9:** The unexplained shift that occurs between the first and the second load cycle, for test TC1, TC2, TC3 has been accepted in the post-processing. This nonphysical "loop" that occurs when the tensile load transitions to unloading, is shown in Figures (75), (76) and (77). It is accepted since it is not evaluated to determine the slope of the curve. Moreover, this behavior was also examined by performing a similar cyclic load with a metal wire, and it resulted in identical behavior. Thus, it must be an error originating from the Short Fiber Testing System and not from the operator or material.

![Figure 75: Post-processing error displaying a nonphysical behavior in experiment with single wood fiber.](image-url)
Figure 76: Post-processing error occurs directly in the raw data in experiments with single wood fibers.

Figure 77: Post-processing error displaying a nonphysical behavior in the experiment with a thin metal wire. Thus, this post-processing error does not originate either from the operator or the type of fiber.
I Technical drawings
Gripper 22A - 8:1
Gripper 23A - 8:1
Paper frame model F5 - scale 2:1

All dimensions in millimeter.