Creasing mechanisms of paper

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Abstract

This present study focuses on creasing of paper. A crease/wrinkle is a buckle which is folded. The goal of this report is to find the influence of variations in grammage/moisture profiles on creasing by means of experiments and finite element simulations.

Creasing may be caused by a weak spot in the paper. Out of plane deformation of the spot occurs because it has a lower stiffness than the rest of the paper. The parameters of the paper type 'Schrenz' are determined in three directions with tensile tests. The used sample size equals the size of the Finite Element model, because of influences of the sample dimensions on the material parameters. These parameters are imported into a Finite Element model, which is used to obtain stress and strain information of a tensile sample.

From the tensile tests it is known that the Young’s modulus of the Machine direction is approximately three times higher than the Cross-direction. The simulated tensile test in M-direction matches with the experimental test.

Two mechanisms that can cause creasing, pre-load and cloud formation and the behavior of paper in a splicer are evaluated. Measurements and observations are performed to determine the influence of these mechanisms. Pre-load and inhomogeneity of fibers (cloud formation) in paper can cause differences in strength and Young’s modulus. Pre-load causes the Young’s modulus to be lower. This is also the case in a low fiber spot in a paper with cloud formation. The buffering process in a corrugator causes instability and therefore shows a high probability of creasing.

From a company which produces corrugated board, samples which showed creasing are investigated by measuring moisture and grammage profiles. The Young’s modulus and the tensile strength are obtained from these samples by tensile tests. Evaluations of the measurements show that the results are not reproducible. Spots where creasing takes place are also not traceable. The measurements show that the moisture-and grammage distribution, Young’s modulus and max stress correlate with each other.

Experiments are conducted to visualize and to measure the deformation of a tensile sample with a weak spot. These experiments are performed with a static and dynamic tensile stage. The same test is also performed with the numerical model to obtain the strains and stresses. The experiments show that under tension a buckle occurs in a sample with a weak spot. Optical Profiling proves that a variation in grammage results in a buckle, which may be the beginning of a crease.
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Smurfit Kappa Paper Services (SKPS) in Roermond manages the customer complaints in Europe concerning the delivered paper products from Smurfit Kappa Roermond Paper (SKRP). SKRP produces various types of recycled paper. One of the complaints is ‘creasing’. Creasing is the wrinkling/buckling of paper.

At the customers, wrinkling of paper takes place in corrugators. Corrugators are machines for the production of corrugated board. Figure 1b shows a sample of corrugated board. If creasing occurs in a corrugator, this causes paper breaks and the production of board is delayed for a certain time. Furthermore, creases damage the surface of corrugated board and the product is not appealing anymore. For SKPS these complaints and the expenses associated with them can be expensive. It therefore has an interest in understanding and preventing the problem.

Most problems are encountered with the paper type ‘Schrenz’. Schrenz is produced from low grade old paper (short fibers) and the fibers are fixated by hydrogen bonds. No glue is used in this process. During paper production it is important to maintain a uniform property profile of the paper. Keeping this property profile uniform can be very complex, because of the involvement of many parameters, such as configuration/alignment of the paper machine, but also the distribution of water and density profiles in the produced paper.

This report discusses the material behavior characterized by several parameters, such as moisture-and grammage distribution. These parameters are believed to be of particular relevance for creasing of paper. Therefore their influence will be examined by numerical and experimental tests.

The local defects, caused by grammage and moisture variations are difficult to comprehend, which leads to the objective of this research: Determine the influence of local defects, caused by grammage and moisture variations on creasing.

In chapter 2 some theoretical background is given on how creasing can be triggered. The next chapter is used to show how some parameters, Young’s modulus and maximum tensile stress, are obtained and how these parameters are implemented in a finite element model. Chapter 4 discusses the influence of different tensile specimen dimensions on the parameters obtained in chapter 3. The following chapter reviews three mechanisms which can cause creasing. Chapter 6 discusses measurements made on samples with creases which were obtained from a company in France. The experiments containing some specially prepared tensile specimens and numerical results are discussed in chapter 7. The last chapter gives a proof that a difference in grammage causes a buckle in a tensile sample. And at the end the report is closed with a conclusion and some recommendations.

![Figure 1: Corrugated board](image-url)
2 Hypothesis

2.1 Mechanisms

There are three important mechanisms that can induce creasing/wrinkling. The first is misalignment of the reel, figure 2a. The reel is a cylinder consisting of rewound paper if it is not properly rewound or it is not placed parallel inside the corrugator, a wavy pattern is emerging at the beginning of the corrugator due to shear stresses in the paper, figure 2b. The second mechanism shows the same behavior as misalignment, but is caused by the fiber orientation in the material. The orientation of the fibers goes from vertical to horizontal from side to side. The third mechanism is due to local deviations of moisture and grammage profiles in the paper, which leads to creasing, figure 3. The latter mechanism will be discussed further in this report.

![Reel and wavy pattern](image1)

Figure 2: Reel and wavy pattern

![Crease in corrugated board](image2)

Figure 3: Crease in corrugated board

2.2 Researched theory

A possible explanation of the occurrence of creasing is given below. It is known that moisture and grammage are of great influence on the stiffness and strength of paper. Variations of moisture and grammage within the paper therefore result in variations of stiffness and strength.

In figure 4, a tensile specimen is shown with two different grammages, distributed in an idealistic way, which is loaded in tension. Suppose that, because of differences in grammage or amount of moisture and E2 has a higher Young’s modulus (stiffness) than E1. When conducting a tensile test, the specimen contracts in the direction perpendicular on the tensile force [1]. This contraction results in a compressive in-plane stress in the more compliant material, which may therefore buckle.
Figure 4: Tensile test on a sample with two different grammages, leading to variations in stiffness
3 Large-scale experiments

For the research on creasing SKSCAO in Bray En Val (France) has been visited. This company uses Schrenz paper to produce corrugated board. Some reels which showed creasing were filmed for further observation in Roermond and rough measurements of the moisture distribution were conducted. Samples were cut from the reels and taken to Roermond for further measurements.

Four parameters have been evaluated: the grammage distribution (density profile over the width), Young’s modulus, maximum stress and the moisture profile. In the next sections the findings will be discussed.

3.1 Influence moisture profile

One reel consisting of paper from Alincourt, used to make corrugated board at SKSCAO at Bray En Val, had an area with a high percentage of moisture (10% against 6% elsewhere). This reel was measured over the whole width by cutting it into 160 tensile specimens of a width of 15 mm. The maximum tensile stress and the Young’s modulus are plotted against the width in figure 5. These values were measured with a static tensile machine.

![Graph](image)

(a) Young's modulus  
(b) Max stress

Figure 5: Results for the paper from Alincourt

The area with the high moisture percentage can not be traced back in the profiles. One explanation is that the paper samples were measured in a climatised lab (50% humidity and 23 degrees Celsius). Probably paper reaches an equilibrium with its environment very quickly. Then the history of the paper’s moisture profile is lost.
3.2 Results: Measurements Schrenz 115

In this subsection a sample of Schrenz 115 $[g/m^2]$ is analyzed, which was taken from SKSCAO. A crease was observed in this reel at a distance of 50 cm from the edge. In figure 6 two pictures of this crease are depicted. The purpose of the measurement of the grammage/moisture distribution, Young’s modulus and maximum stress over the width of the reel, is to correlate the crease, with deviations in the measured values. Figure 7 shows the measurements; see appendix B for a discussion on how these measurements were processed.

Figure 6: Schrenz 115 of a width of 2.35 [m] in the corrugator at Bray En Val

Figure 7: Results of Schrenz 115 with a width of 2.35 [m]
Evaluating the results, the crease can not be identified in the measured profiles. At approximately 20 and 150 cm from the edge (in figure 7, 0 = edge) some deviations are observed, but at these spots no creasing occurred.

From the results it is visible that the grammage, maximum stress and the Young’s modulus correlate. To check if these results are reproducible, new measurements were conducted a little further down the reel, only the first 60 cm from the edge were measured. Figure 8 gives the outcome for the first and the second measurement. The values from the two tensile tests are different. This is due to a high noise level in the measurements. This proves that these measurements are not reproducible and can not be used to predict creasing.

![Figure 8: Difference in Young’s moduli over the M-direction in a reel](image)

The grammage is measured by hand, but a scanner in Paper Machine 2 (PM2) also measures the grammage. Figure 9 displays both measurements. The profiles are not exactly the same, but the overall shapes show some similarity. The measurements from the machine are mean values because the values are scanned over a certain length. With this scanning method the overall grammage is controlled, but it is not appropriate to trace areas sensitive for creasing. The method has a high noise level and too few points are measured during a scan over the width in the paper machine. The paper flows continuous with a high speed while the scanner scans from one side to the other side. In this way the grammages over the width over a certain length is measured.
It is known from practice that reels of 2.35 [m] width tend to crease more than reels with a width of 2.20 or 2.50 [m]. This is observed at SKSCAO. Hence, also a sample of Schrenz 115 with a width of 2.50 [m] was measured. This reel did not crease. Figure 10 shows the outcome of these measurements. The grammage and the Young’s modulus are a little higher than the results of Schrenz 115 with a width of 2.35 [m]. But the overall profiles are the same.

The measurements in figures 7 and 10 prove that the paper properties of reels with a different width are the same. This suggests that easier creasing of paper having a width of 2.35 m is not due to different properties.
Figure 10: Results of Schrenz 115 with a width of 2.50 [m]
4 Lab-scale experiments

4.1 Parameter determination of Schrenz

To get an idea of the strength of the paper 'Schrenz' and to obtain some important parameters for the numerical simulations, static tensile tests are performed. The sample sizes of the used tensile specimens are respectively $30 \cdot 30 \cdot 0.18 \text{ [mm]}$ (length \cdot width \cdot thickness). A large sample shows more creasing, that is why the width of the sample is chosen the same as the maximum width of the tensile clamps, $30 \text{ [mm]}$.

4.1.1 Tensile tests in three directions

First, tensile tests in three different directions are performed. In Machine direction (MD), Machine Cross direction (CD) and under 45 degrees with the Machine direction (45MD). The displacement rate is $20 \text{ [mm/min]}$, this is a standard in the paper industry. From these different tests the Young’s modulus, the maximum stress and the breaking length of the samples are obtained. The first two can be used as parameters for the numerical model. Figure 11 shows the results of the static tensile tests. The dashed lines, which have been fitted to the first part of each response, represent the different Young’s moduli. Table 1 gives the calculated values.

![Figure 11: Tensile test in three directions](image)

<table>
<thead>
<tr>
<th>Direction</th>
<th>Young’s modulus [MPa]</th>
<th>Maximum stress [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>MD</td>
<td>1620</td>
<td>18.2</td>
</tr>
<tr>
<td>CD</td>
<td>640</td>
<td>7</td>
</tr>
<tr>
<td>45MD</td>
<td>860</td>
<td>8.5</td>
</tr>
</tbody>
</table>

Table 1: Measured material parameters
4.1.2 Influence of sample dimensions

Different dimensions of the test specimens give different results during the uniaxial in-plane tensile tests. Theoretically, one would expect the same stress/strain curves using different sample sizes, due to the used dimensionless strain, the engineering strain $\varepsilon = \frac{\Delta L}{L_0}$ and the engineering stress $\sigma = \frac{F}{A}$, where $L$ and $A$ are the length and cross-sectional area of the sample, $\Delta L$ it’s elongation and $F$ the force needed to impose this elongation. Because of the engineering stress and strain only geometrically linear analysis are conducted. Figure 12 shows that for different widths of the sample different stress-strain curves are obtained. For a higher length of the sample, the maximum strain is lower. Also if the width of a test specimen is smaller, the maximum stress is higher.

![Stress-strain curves](image1.png)

(a) In – plane stress – strain curves  
(b) Two formats

Figure 12: Influence of different sample sizes on stress and strain, a: In-plane tensile responds width five different widths of the tensile specimen, b: Two different formats, the longest tensile specimen has the lowest strain

Now it is known that the dimensions of a tensile specimen are significant for the determination of the material parameters for the finite element model, all tensile samples used are equal in size to the finite element model.

4.1.3 Finite Element Model

To simulate the paper behavior with a finite element model, the program ‘Marc-Mentat’ is used. This program calculates the strains and stresses occurring in a deformation process. In this program the material model ‘Hill48’ is chosen, because this model contains orthotropic elastic behavior and an orthotropic yield with orthotropic hardening. Therefore this material model is appropriate to simulate the orthotropic behavior of paper [2]. The finite element model supports the interpretation of the experimental results. It is also used to visualize cases with different material properties and/or shapes. To show that this finite element model is a good approximation of reality, a numerical tensile test in machine direction is simulated and plotted in figure 13 together with the result of an experimental tensile test in machine direction. The numerical stress is: $\sigma = \frac{F}{A_0}$, where $F$ is the calculated reaction force and $A_0$ the initial cross-section of the tensile specimen.
Figure 13: Numerical tensile response virtually coincides with experimental response

Figure 13 shows that tensile response of the finite element model and the experimental model virtually coincide with each other. This demonstrates that the material behavior of this finite element model is appropriate to simulate ‘Schrenz’ paper. Therefore this model can be used to predict stresses and strains in a sample before an actual experiment.
Figure 14 displays the stress and strain distribution in a finite element model of a tensile specimen with a weak spot in the center (heterogeneous sample) and a homogeneous sample (no weak spot). This figure shows an in-plane compression of the weak spot in Y-direction, when a displacement of 1 mm in X-direction is applied to the tensile sample. In the homogeneous sample also in-plane compression is visible but distributed over the whole width, which shows that this cannot lead to buckling. The results give an impression what can be expected in the experimental set-up. From figure 14 it is expected that the compression in the weak spot leads to buckling in experimental tests. In appendix C more numerical results are given.
4.2 Creasing mechanisms

In the next sections the origins of some local errors are discussed. Inhomogeneity of the fiber distribution in a paper web, the so called ’cloud formation’ leading to grammage differences will be discussed, but more profundity in later chapters. In the third section buffering in a splicer is discussed. This is not a creasing mechanism, but an aspect which is also important, especially the dynamic influence this machine has on paper.

4.2.1 Pre-load

A question is if strains in a reel (cylinder consisting of rewound paper) can cause weak points/areas. These strains can develop when dirt enters the reel during rewinding or if the rewinder is not well aligned. In both cases, this causes the perimeter to increase and strains may develop.

The influence of the pretension similar to that induced in a reel is investigated on a tensile specimen in the paper lab at SK Roermond by giving it a certain strain. This strain is held for 2 minutes and then the specimen is relaxed and a tensile test is executed until the sample breaks. Figure 15 shows that the Young’s modulus is reduced by approximately 120 [MPa] for specimens with pretension compared to normally loaded specimens. The tensile curves represent a mean value generated out of 10 tensile responses.

![Figure 15: Difference in Young’s modulus between pre-loaded sample and normally loaded sample](image)

Because of a strict time schedule it has not been established if this reduction can cause creasing.

4.2.2 Cloud formation and grammage

Cloud formation is introduced by the head box (Material input) at the beginning of the paper machine. Cloud formation causes differences in density/grammage, this can be seen in figure 16. Clouds consist of areas with a higher number of fibers, inducing differences in strength and stiffness. To observe the maximum difference in strength between a spot with a high concentration of fibers and a spot with a low concentration, measurements of these spots have been conducted. The samples were cut out of the paper at three locations with different concentrations of fibers, high and low concentrations and some samples were cut randomly to get an average distribution. The measurements on these samples were
performed with a static tensile machine and yielded the results depicted in figure 17. Table 2 gives the maximum stresses and the Young’s moduli of the different areas.

![Figure 16: Cloud formation in two different papers, the darker areas represent high concentrations of fibers](image1)

(a) *Paper Alincourt*  
(b) *Paper Schrenz*

Figure 16: Cloud formation in two different papers, the darker areas represent high concentrations of fibers.

![Figure 17: Strength differences associated with cloud formation](image2)

![Graph showing stress vs. strain with different fiber concentrations](image3)

Figure 17: Strength differences associated with cloud formation.

### Table 2: Cloud formation

<table>
<thead>
<tr>
<th>Fiber Concentration</th>
<th>Maximum Stress [MPa]</th>
<th>Young’s Modulus [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>High concentration fibers</td>
<td>18.7</td>
<td>1364</td>
</tr>
<tr>
<td>Average concentration fibers</td>
<td>17.4</td>
<td>1320</td>
</tr>
<tr>
<td>Low concentration fibers</td>
<td>16.7</td>
<td>1290</td>
</tr>
</tbody>
</table>

Variations in fiber concentration in the paper cause a maximum difference of 11% in tensile strength. Also the Young’s modulus reduces with 5.4% from a high to a low concentration of fibers. If this has an influence on creasing can not be confirmed.

#### 4.2.3 Buffering in splicer

When observing a corrugator, and especially the splicer at the beginning of this machine, one may observe creasing. The splicer, figure 18, creates a buffer so that the board production can continue seamlessly when paper reels are changed. When the buffer has its maximum size the paper in it turns to be more sensitive to creasing. This is due to the
long distance between the rolls of the buffer. This makes the paper flow unstable. This ‘buffering’ is not a mechanisms, but a configuration that makes the paper more sensitive for local errors

Creasing is also observed if the paper is accelerated in the corrugator, this causes higher stresses which may result in creasing.

Figure 18: Splicer, the first part of a corrugator [3]

A corrugator has influence on the creasing of paper. The buffering process makes the paper unstable and more sensitive for creasing. Accelerations and decelerations of the paper in the corrugator also lead to creasing. In this research only the influence of the paper properties on creasing are evaluated. More research of the influence of the corrugator is needed to prove if it really has an influence on creasing.
4.3 Grammage variation on lab-scale

Because the measurements in a reel are not reproducible, a better defined measurement is needed. In the remainder of this report we focus on the initial stages of crease formation and attempt to recreate these stages on a small scale in a tensile test and in simulations. Inducing a crease on a tensile machine is not feasible, but buckling (the beginning of creasing) is. Normally if a buckle rolls over a roller it is folded and results in a crease. The method followed is to prepare data from samples with different weak spots due to a lower grammage. The samples consist of a tensile specimen with a weakened spot in the middle. Buckling may occur if a strain is applied to the paper, because of differences in stiffness. In the next section the preparation of these test samples is discussed. The last two sections discuss the results of the experiments and numerical simulations.

4.3.1 Sample preparation

From chapter 2 it is known that the grammage, Young’s modulus and the maximum tensile strength correlate. Also the moisture percentage can be correlated to the grammage. For this reason the choice is made to simulate variations in the paper properties by creating a weak spot by removing fibers from the surface.

To induce these weak spots in a tensile bar different brands of adhesive tapes are used. Appendix A gives a table with the values of removed weight of fibers per brand of tape. From every tape circular shapes with a diameter of 10 [mm] were punched. The established round shapes were applied to the tensile specimens and compressed with a weight of 5 Kg for 1 minute. subsequently, the tape was removed from the paper thus removing some fibers, see figure 19. In this way a weak circular spot with a diameter of 10 [mm] was established in the tensile specimens of 30 · 30 mm². To know how much fiber material was removed, every specimen was measured before and after the tape was applied. See figure 20 for a sample of tape with fibers. The tensile sample has a width and length of 30 [mm] and a thickness of approximately 0.18 [mm].

Figure 19: Preparation of samples
4.3.2 Experimental results

Tensile tests have been conducted on the samples having a successive weaker spot. Figure 21 shows that the maximum tensile stress decreases with the weight reduction due to the weak spot.

![Figure 21: Influence on the maximum stress of variation of the grammage in a local spot](image)

The tensile tests were filmed to examine the deformation around the weak spot. When a buckle was observed during the test, this was noted. Limits could thus be established beyond which grammage difference between the weak spot and the remaining sample a crease occurred. These differences are compared with the largest grammage differences.
in Schrenz paper having a width of 2.35 m. Figure 22 shows a tensile sample without a weak spot remaining flat under tension. The sample with a weak spot clearly shows some out-of-plane deformation under the same amount tension. This is one of the samples used to obtain figure 21.

4.3.3 Cyclic tensile test

It is difficult to get good results with a static tensile machine, because the samples break easily. Therefore a cyclic tensile machine [4] has also been used. Buckling is easier established and the dynamic loading by a the corrugator is simulated more realistically.

In the beginning of the test a certain static force is applied on a tensile specimen of $30 \times 90 \times 0.18 \text{ mm}$. A force of approximately 100-110 N, followed by an oscillating amplitude between 0.5 and 0.3 mm with a frequency of 1 Hz, see figure 23. This causes the specimen to stress and relax. After a few periods a buckle appears and finally the sample breaks. Figure 24 shows a buckle induced by such a cyclic tensile test.

![Cyclic loading of a specimen](image)

Figure 23: Cyclic loading of a specimen

![Buckle induced by cyclic test](image)

Figure 24: Buckle induced by cyclic test

Inducing a buckle with this method is easier if the sample must stay intact. Results with different weak spots have not been obtained. Still, a cyclic test visualizes the de-
creasing strength of a paper sample per cycle. This mechanism is also experienced by the paper in a corrugator and the splicer at the beginning of the corrugator.

4.4 Optical profiling

To prove that a buckle really can occur because of a local weaker spot, a test at the Technische Universiteit Eindhoven (TU/e) was performed using optical profiling. Optical profiling is conducted with a microscope and gives a topographic profile of the sample surface. Figure 25 shows that the sample is scanned perpendicular to the tensile force. Not the full 30 mm over the width are scanned, this is because of limits of optical profiling. The following three samples were used: a sample of Schrenz 100 (weak sample), a sample of Schrenz 115 and a sample of Schrenz 115 with a weak spot, called the heterogeneous sample, figure 26. If the strong (Schrenz 115) and the weak sample (Schrenz 100) do not buckle in the tensile test and the heterogeneous sample does buckle, the proof is given that it is the variations of properties which introduces buckling. In the next section some more information is given about the prepared samples.

![Figure 25: Profile scanned on the line perpendicular to the tensile force](image)

![Figure 26: Schrenz 100 (weak sample), Schrenz 115 and heterogeneous sample](image)

4.4.1 Sample preparation

Making a little weak spot with tape is not so hard. But when the surface of the pulled fibers needs to be larger, such as in the uniformly weakened sample, it is easy to break the sample when tearing the tape off. Fortunately the weak spot created in Schrenz 115 has almost the same properties as Schrenz 100. Figure 27 shows that the tensile response of the two is almost identical. The maximum stress of the weakened Schrenz 115 is a little lower because damage occurred while the samples were prepared. The small weak spot will behave more like Schrenz 100, because almost no damage occurs when preparing the heterogeneous tensile specimens. Therefore, Schrenz 100 is chosen as the homogeneous sample to represent the weak spot in the heterogeneous sample.
Figure 27: Comparison Schrenz 100 and Weakened Schrenz 115

4.4.2 Optical profiling results

Figure 28 shows the out-of-plane displacement of the heterogeneous sample when it is loaded by 20 [N] and 90 [N]. At 20 N the sample is almost flat. But when a higher force is applied the paper tends to buckle. The out-of-plane displacement is approximately 0.5 mm. In reality this could be the beginning of a crease.

Figure 28: Out-of-plane displacement of the heterogeneous sample, at 20 and 90 N
Figure 29: The heterogeneous sample (sample with weak spot) buckles, the other samples remain approximately in-plane at 90 N

If figure 29 is taken into account, it is clear that when a tensile test is conducted on a sample of Schrenz 100 or Schrenz 115, both being more or less homogeneous, these samples remain flat. Only the heterogeneous sample (two different material properties) shows a considerable out-of-plane displacement. This proves the statement that a weaker spot induces buckling.
5 Discussion, conclusions and recommendations

5.1 Discussion

This report discusses the influence of variations in grammage and moisture profiles on creasing. The stiffness and strength of a low grammage or high moisture spot is lower. The working hypothesis is that such variations in properties contribute to the formation of creases.

A physical model and a finite element model have been made to study the deformation near such a local weak spot. From these results it is predicted that, contrary to a homogeneous material the material with a weak spot will come out of the plane of the paper under tension. To make the finite element model, the Young’s modulus and the maximum tensile stress are needed. These parameters, obtained from tensile tests, are sensitive to the sample dimensions. The tensile specimens are chosen to have the same dimensions as the finite element model.

Pre-load and inhomogeneity of fibers (cloud formation) in paper can cause differences in strength and Young’s modulus. Pre-load causes the Young’s modulus to be lower. This is also the case with a low fiber-density spot in a paper with cloud formation. A third mechanism that influences creasing is the buffering process in a corrugator. This causes instability and the probability of creasing increases.

An evaluation of the measurements on paper from Bray En Val shows that the results are not reproducible. Spots where creasing takes place are also not traceable. The measurements show that the moisture and grammage distribution, Young’s modulus and maximum stress correlate.

In the small-scale experiments, samples with weak spots were prepared and tested on a static stage. It is possible to introduce buckles in those samples. But a cyclic tensile test is more efficient to use and can be used to imitate the behavior of a corrugator.

At the TU/e more of these test are performed on a Micro Tensile Stage under a microscope. Optical profiling is used to visualize the topography of the paper specimens. This test proves that a combination of two different properties (grammage) results in a buckle, which may be the beginning of a crease.

5.2 Conclusions

- The maximum tensile stress and the stiffness reduces in a spot having a high moisture percentage or a lower grammage.
- A finite element model is created, which contains the material behavior of paper. This model predicts that paper comes out of plane under tension.
- The parameters, Young’s modulus and tensile stress, are sensitive to different tensile sample dimensions. The tensile samples equal the size of the finite element model.
- Pre-load and a low concentration of fibers causes the Young’s modulus to reduce.
- Buffering in a corrugator makes the paper more sensitive for creasing.
- Measurements in paper show that moisture, grammage distribution, Young’s modulus and maximum tensile stress are dependent on each other. But measurements are not reproducible. Creasing can not be traced in these measurements.
- Buckles can be introduced with tensile tests in samples with a weak spot. The dynamic test is more efficient than the static tensile test.
- Optical profiling proves that buckling only occurs in a sample containing two different material properties. A sample containing the same properties remains flat.
5.3 Recommendations

The following recommendations are given to improve this research:

- This report discusses the influence of the paper on creasing. A report of the influence of a corrugator on creasing would be of great value. Which of the two can control the creasing process with less effort and low cost.

- Scanning the paper on grammage and moisture which is done now is sufficient to control these two in the paper machine. If the grammage has an influence on creasing, the control has to be more precise, a higher sample frequency is preferred. The best is a method which measures one hole width in one scan.

- The tensile specimens with a weak spot are difficult to make. A successor should find a better method, especially how to control the number of fibers taken off.

- A research has to be performed if the deviations due to pre-load and cloud formation are sufficient to induce creasing.
References


A Adhesive tape

In table 3 the weight reduction is given by pulling of a circular tape with an area of 78,5 mm$^2$ after it is pressed for 1 minute by a weight of 5 Kg. This table helps to find the appropriate tape for a proper weight reduction to make a weak spot. As an example: If you want to make a weak spot of 100 g/m$^2$ in a paper of 115 g/m$^2$. The weight reduction has to be 1,2 mg. 3M tape can be used to create this spot, by reducing the pressure time a little.

<table>
<thead>
<tr>
<th>Brand of tape</th>
<th>Weight reduction [mg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tesa double</td>
<td>0.9</td>
</tr>
<tr>
<td></td>
<td>0.7</td>
</tr>
<tr>
<td></td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td>1.4</td>
</tr>
<tr>
<td>Red/white</td>
<td>0.8</td>
</tr>
<tr>
<td></td>
<td>0.8</td>
</tr>
<tr>
<td></td>
<td>0.3</td>
</tr>
<tr>
<td></td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td>1.2</td>
</tr>
<tr>
<td>3M double</td>
<td>1.3</td>
</tr>
<tr>
<td></td>
<td>1.8</td>
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<tr>
<td></td>
<td>1.5</td>
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<tr>
<td></td>
<td>1.3</td>
</tr>
<tr>
<td>Coumann</td>
<td>1.1</td>
</tr>
<tr>
<td></td>
<td>0.6</td>
</tr>
<tr>
<td></td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td>0.7</td>
</tr>
</tbody>
</table>

B M-file to process measurements

A m-file is made to use Matlab to process the measurements conducted on a tensile machine. This file shown beneath can be used to plot strain-stress curves and it calculates the Young’s moduli of these curves.
%SCAO metingen eerste strook Backside (linkerkant) papier
%close all
%clear all
n=1
Ealles1=[]
e11=[];
e12=[];
Maxtotaal11=[];
Maxtotaal12=[];
for n=1:2:22
    for k=n %alleen oneven getallen, omdat telkens 2 metingen van hetzelfde strookje papier zijn
        file=['Brayen235val' num2str(k),'.tra'];
        fid=fopen(file);
        [totaal] =textscan(fid,'%f%c%f%c%f','headerlines',4);
        fclose(fid);
        stressstrain=[totaal{1},totaal{5}];
        i=length(stressstrain);
e1=stressstrain(i,2);
e11=[e11,e1];
t=k+1;
Max=max(totaal{5});
Maxtotaal11=[Maxtotaal11,Max];
    end
    for s=t
        file=['Brayen235val' num2str(s),'.tra'];
        fid=fopen(file);
        [totaal] =textscan(fid,'%f%c%f%c%f','headerlines',4);
        fclose(fid);
        stressstrain1=[totaal{1},totaal{5}];
        j=length(stressstrain1);
e1=stressstrain1(j,2);
e12=[e12,e1];
Max1=max(totaal{5});
Maxtotaal12=[Maxtotaal12,Max1];
    end
l=[length(stressstrain),length(stressstrain1)];
L=min(l);
Maxtotaal1=(Maxtotaal11+Maxtotaal12)/2;
strain1=stressstrain([1:L],1);
stress1=stressstrain([1:L],2);
strain2=stressstrain([1:L],1);
stress2=stressstrain([1:L],2);
matrix11=[strain1,stress1];
matrix12=[strain2,stress2];
Matrixtotaal=[matrix11+matrix12];
Matrixgem=Matrixtotaal/2;
C Numerical results

Figure 30 shows the stress and strain distribution in the x-direction in a finite element model with a weak spot. These strains and stresses are calculated by a displacement of 1 mm in x-direction. The strains in the weak spot are very high, whereas the stresses are reasonably low.

(a) Strain x – direction

(b) Stress x – direction

Figure 30: Response of the finite element model by a displacement of 1 mm in x-direction