Development of a 4-point bending test to characterize creases on paperboard and packaging material.

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DIVISION OF PRODUCT DEVELOPMENT | DEPARTMENT OF DESIGN SCIENCES
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MASTER THESIS

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Abstract

During the manufacturing of a paperboard-based package, the material is in one step folded to obtain the desired shape of the end product. Prior to this step, the material undergoes another processing step, creasing, in which the material is damaged along the folding lines. The result of the creasing process is that the material delaminates which, in turn, causes the material to fold in smooth lines without any wrinkles or cracks along the edge. The strength of the crease can be measured to ensure the creasing has been done correct.

This thesis will focus on developing a new method for evaluating creases using four-point bending, as the current method has flaws in that it is operator dependent and the bending is not taking place under ideal conditions. The first part of the thesis will focus on investigating the effect of different parameters and based on this suggest a new method for measuring the strength of the crease. The second part will focus on comparing the same suggested method to the current one and the first iteration of the four-point bending method used at Tetra Pak.

Among the parameters tested, the parameters that significantly affected the maximum force registered during the bending was the different materials, the stiffness/thickness of the sample, MD or CD direction, if the bend was performed inside to inside or outside to outside and in the case of a thick material the position of the crease between the loading pins. The time it took to perform the measurements were fastest using the suggested method. The value of the strength of the crease was however significantly

Popular science abstract

At Tetra Pak, the goal is to produce appealing, high quality packages that protects the food within. There are a lot of ongoing projects with the sole purpose of ensuring that the correct standard of all the products produced is achieved.

This project has been made with the purpose of in the end ensuring the visual and perceived quality of a paperboard-based food package. This was done by designing a new quality measurement tool to measure the strength of the packaging material where it will be folded. A too strong package will be hard to fold without ruining the smooth appearance of the package and a too weak package will not be able to maintain the mechanical properties required of the material.

The findings in this project will provide the quality inspectors with an easy to use tool that, no matter who uses it, will give a reliable and correct value of the strength of the package, to ensure that the folding is performed in a correct manner.

To the everyday eye, a paperboard-based package will always look the same, and not much thought is put into the subject of misformed packages in the shelves at the grocery stores. However, the end product of unwanted packages in the shelf is waste, both in the form of food, but also the material and all energy required to produce these two. This is avoided to a large extent solely due to the fact that the material has undergone several steps of scrutinization during the development of the package. This new tool is aimed towards the people doing these measurements, in that it hopefully will give a more accurate way of doing these measurements while also also saving time in the process.

The end result will hopefully be a new, better, way to characterize the material properties, that in the end results in a more efficient working climate, resulting in more time spent to make new, revolutionary, findings in the area of paperboard-based packages.

The suggested method found in this report is only a scratch on the surface and to fully uncover the potential of four-point bending within this area, additional research needs to be done.

Keywords: Crease strength, four-point bending, method development, operator independent

Acknowledgements

I would like to thank my supervisors at Tetra Pak Johan Wickström and Christel Andersson as well as my supervisor at Lunds Tekniska Högskola Annika Olsson for their support and guidance throughout this master thesis.

I would also like to thank my friends for providing me with the social interaction which kept me sane throughout the entire work.

A special thanks to Freja Milton for providing me with coffee every morning, which without, this report would not have happened. At least not in an enjoyable way.

Preface

Although my field of expertise lies within the food sector, I chose to do my master thesis within method development in an area that I had little to no prior knowledge in when the opportunity was given to me.

Although it has been hard during times, I do no regret my choice of collaborating with Tetra Pak in finishing my studies to become a civil engineer.

Lund, 07-2018

Jakob Lindbladh

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1 Introduction

When a laminated paperboard package is produced by Tetra Pak, the material undergoes several steps of processing. One step prior to the folding of the final package is creasing. During the creasing process, the material is intentionally damaged to cause the material to delaminate in the zones where the folding will happen. The creasing is performed to ensure that the folds will be smooth without any wrinkles or cracks along them (Huang, H et al, 2014). However, if the material is creased too hard, it can lose its mechanical properties (Iggesund, 2018).

To ensure that the creasing is done correctly, e.g. the material is not too little or too much damaged, the strength of the crease is measured and compared to the strength of the uncreased material.

Today this is performed using a method called I003.5 in which the sample is clamped a certain distance from the crease and then bent. A load cell registers the maximum force obtained during the bends and the quota is calculated (Hansson L. 2018). As the creases can be hard to detect, the set distance at which the sample should be clamped can be hard to specify, making the method operator dependent. This is especially true for creases with complex geometries. Due to the clamping of the sample, it can no longer move freely. This means that the bending is not happening under ideal conditions and the method does not necessarily reflect the truth. (Gullichsen et al., 1999).

A new alternative testing method to the current one is four-point bending. This method has the advantage of distributing the load evenly over a section of the sample, which leads to the method being less sensitive to incorrect placement of the sample as the material always will fail at the weakest point of the loaded region (Beex, L. and Peerlings, R, 2009). The method can be carried out on an ordinary universal tester and more complex geometries can be tested compared to I003.5 due to how it is performed. The method could potentially also be used to predict the forming of the package.

This master thesis will be divided into two sub studies, the first one with the aim of identifying which parameters that can affect the recorded force using four-point bending and test those for a statistical impact on the result. Then based on the results, present a new method for investigation of the strength of the creases. The second study will be a verification study in which the proposed method will be compared to the old method, manual I003.5, and the first version of a four-point bending method developed at Tetra Pak. The comparison will cover time and the measured values of the different methods.

2 Theoretical background

2.1 Structure of packaging material

The definition of paperboard is paper with a weight of at least 200 g/m^2. The paperboard is often constructed of multiple plies that together defines the material. This results in that paperboard can be tailored after its supposed purpose by choosing the different plies accordingly (Savolainen, 1998; Mullineux, Hicks and Berry, 2012). For the paperboard to be modified to a greater extent, at least three plies are required as the main responsible ply for stiffness and converting processes is the middle ply. A normal composition of a paperboard is to have long and strong fibers in the outer layer while having bulky fibers in the middle to ensure the stiffness and strength (Iggesund.com, 2018).

Layers of different polymers and aluminum foil can be added to the paperboard to add properties to the package that paperboard is uncapable of, such as protection against light, moisture and gases that would otherwise damage the packaged goods. This kind of material is often referred to as packaging material or laminated paperboard (Savolainen, 1998; Tetrapak.com, 2018). An example of the different materials that can be found in a paperboard package can be seen in Figure 1 below.

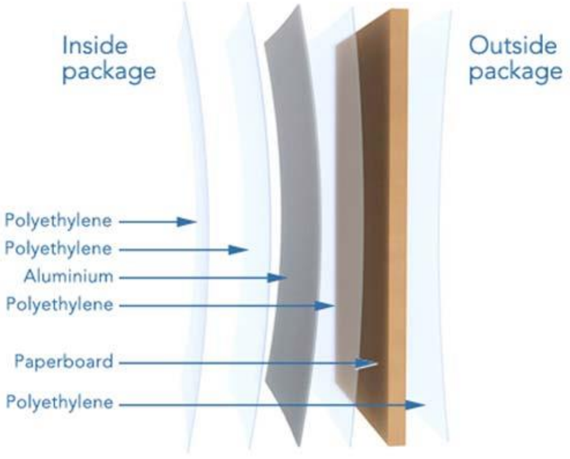

Figure 1 The different plies of materials add different properties to the package.

2.2 Directional properties of paper and paperboard

Due to the way paper and paperboard is manufactured, the material is anisotropic. The result of this is that the material can have mechanical properties that is 1-5 times higher in the machine direction (MD) compared to the cross direction (CD). Likewise, mechanical properties of the MD can be around 100 times higher than that of the ZD direction (Li et al., 2016). The different directions of the roll can be seen in Figure 2.

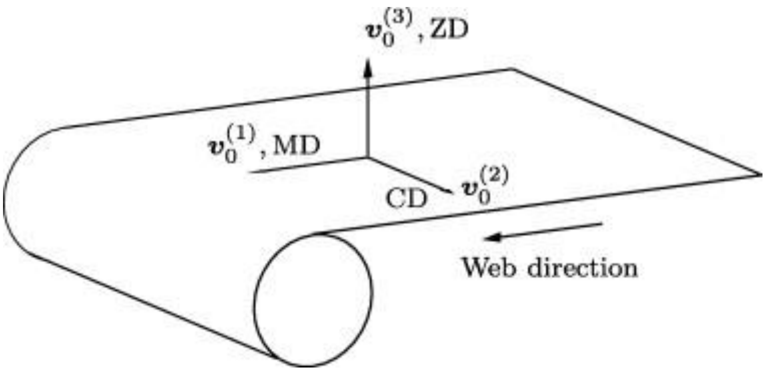

Figure 2 The different directions of the material.

2.3 Creasing

To make the final package look appealing to the customer, the folds e.g. the edges of the package, should be smooth without cracks and wrinkles. This is prevented by creasing the packaging material prior to folding it (Mullineux, Hicks and Berry, 2012).

Creasing is performed on the paperboard to ensure delamination at the critical positions of the material, e.g. the edges of the finished package. Delamination is the phenomenon where the material separates into several thinner layers. This affects the mechanical properties of the material and in the case of paperboard, acts as a hinge to get a good fold. If the material would not have been creased before folding, cracks and wrinkles in the paper are likely to appear. These cracks are random throughout the fold and can affect the forming of the package by causing deformations in the corners of the package (Huang, Hagman and Nygårds, 2014). The crease can also be off center which happens when the creasing tool is not centered. This can happen due to unsynchronized movement of rollers or misalignment during mounting. The crease will then be asymmetrical which can cause the fold to be unsatisfactory and can lead to changes in the packages dimensions. A crease that is heavily off centered can cause the board to break. The creasing can also be too harsh on the material which can cause it to crack (Savolainen, 1998). The crease can also be too deep, causing the surface plies to crack. This also results in a defect package (Iggesund, 2018). A figure depicting a miscentered crease being made can be seen in Figure 5.

However, as the creasing is performed to damage the structure of the material, a material that is creased too hard will lose too much of its mechanical properties which also can result in low stackability due to mechanical failure (Iggesund.com, 2018). A crease should not externally damage the material, but weaken the structure inside the material (Mullineux, Hicks and Berry, 2012). Figure 3 is a schematic model of an uncreased and a creased material being folded. Paper and paperboard converting 231-234

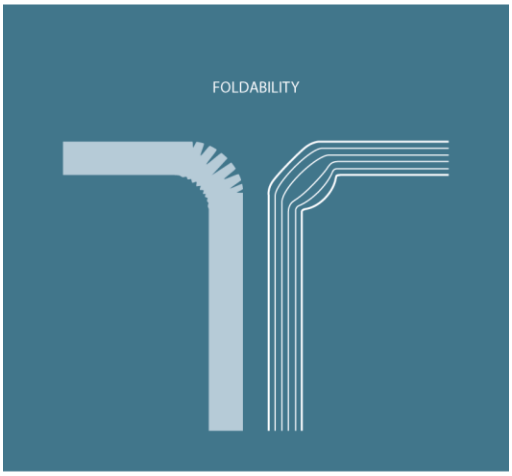

Figure 3 A schematic figure of a material that has not delaminated (left) and one that has (right).

The creasing is performed by a tool consisting of a male and a female die. The female die is a groove in which the male die will push a rule. The material is then placed between the two and they are pressed against each other, forcing the material to be shaped according to the creasing tool (Savolainen, 1998; Iggesund.com, 2018). The general setup can be seen in Figure 4.

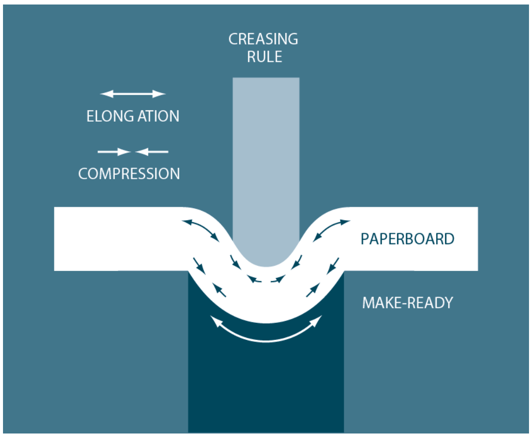

Figure 4 A schematic figure of a creasing tool with the creasing rule pushing down into the groove.

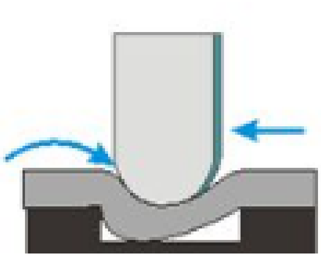

Figure 5 An uneven miscentered crease being made due to misaligned ruler and groove of the creasing tool.

A good crease should act as a hinge during the folding step. This is obtained when the material has delaminated into several thinner plies in the creased area while the outer plies are not damaged. To achieve this, it is important to consider the properties of the area that is to be creased. The thickness and type of paperboard and its direction should be considered to design the width and depth of the crease. The crease should also be able to be made in quick succession as to make the creasing efficient in the production (Savolainen, 1998; Iggesund.com, 2018).

2.4 Measuring the strength of the crease

As an internal quality test to ensure the creasing tool has caused the material to delaminate in the wanted fashion, the strength of the crease can be measured. There are a few different ways to measure the strength of a crease, but they all share the general idea of comparing the bending force required to bend a creased material and comparing that to an uncreased one. When using the folding factor seen in equation 1, the crease is considered good when F is above 50 % (Iggesund.com, 2018). Another way of measuring the crease strength can be seen in equation 2, which is the one used at Tetra Pak.

Equation 1 $$F = \left(\frac{Bending\ momenet_{Uncreased}}{Bending\ moment_{Creased}}\right) * 100$$

Equation 2 $$RCS\ (\%) = \left(\frac{Bending\ force_{Creased}}{Bending\ force_{Uncreased}}\right) * 100$$

There are a few different testing methods available for testing the bending stiffness of paperboard. They can be divided into static and dynamic test methods. The static ones are two-point bending, three-point bending and four-point bending. The dynamic one is the resonance method. Measuring the bending stiffness can also be done by using droop.

Two-point bending is one of the most commonly used techniques although it does not necessarily reflect the truth due to it not following the theoretical conditions of pure bending. Because of this, the method is often referred to as bending resistance. The method is based on clamping one end of the sample and forcing the other to deflect a certain amount. The force required for the sample to deflect is then recorded. Even though the method is not entirely legit, it is good enough to be considered satisfactory when measuring the bending stiffness (Gullichsen et al., 1999).

Three-point bending has not much use in the area of paper and paperboard due to the fact that it can be hard to find the weakest spot of the heterogenous paperboard material (Gullichsen et al., 1999).

In resonance testing, the sample is clamped at one end and is then left to vibrate at a constant frequency. the advantage with using a dynamic test method is that since paper is viscoelastic, the stiffness is higher when the force is presented under a shorter time than if it would have been over a longer time. A problem with this test is however that it has a high variation coefficient which can hide significant differences in bending stiffness (Gullichsen et al., 1999).

Another way of testing is droop. In this method the sample is clamped at one end and left to hang 90 degrees out into thin air and bending under its own weight. The deflection is then recorded by an optical instrument and the stiffness can be calculated. This method, just like the two-point bending and the resonance test, does not measure the bending over the entire sample but only close to the clamped area. The method is also flawed in that it interacts poorly with curled samples (Gullichsen et al., 1999).

2.5 Four-point bending

In four-point bending, the flexural stress of the sample is evenly distributed in the region between the inner loading pins (given that the loading pins are applying the same force on the sample (Asfaltblij.nl, 2018)). This makes the four-point bending test suitable for measuring the bending force of heterogenous materials, such as paperboard and packaging materials, where the weakest point is not known (Pratt, 2018). Likewise, if a creased sample is exposed to four-point bending, the sample should always break in the crease due to the damage done to the material by the creasing tool. This also means that the sample is not as dependent on the positioning during the test as the crease should be placed somewhere between the loading pins and not in relation to a clamp (Beex and Peerlings, 2009). A test method where the sample is less sensitive to the placement could possibly mean that the method is not operator dependent.

However, this also means that the sample must be cut with care as to keep the edges parallel as the weakest point otherwise would be the narrowest part of the sample.

There are a few factors present during four-point bending that affects the outcome of the measurements. There are two phenomenon that are involved in the bending procedure, deflection due to shear and deflection due to bending. In four-point bending, it is assumed that pure bending is happening due to the bending due to shear can be neglected (Pronk, 1996). However, studies have shown that the bending due to shear, albeit low, does in fact affect the result of the measurements (Pronk, 2009). The points in which the force is transmitted are also a source of error as they affect the strained section of the sample when bent. The angle at which the sample is forced into due to the pins in relation to the starting position also affects the outcome (Mujika, 2006). The pins are also responsible of the friction present in the method which does have an impact on the outcome (Schöngrundner et al., 2015). Other parameters affecting the end results are thickness of the sample, adopted strain range and moving parts such as overhanging flaps of the sample and loose parts in the equipment (Mujika, 2006) (Pronk, 2009).

For some materials, mainly spring steel and material with a high polymer amount, a large deflection can be achieved while still being in the elastic limits of the sample. If this is the case, the samples do not follow the linear bending curve but rather a different function. For this function to be correct, it is essential to account for the friction as friction increases the loadbearing performance of the beam. The horizontal distance between the loading pins affect the curvature and therefore the outcome of the measurement, this is not the case in the linear bending theory (OHTSUKI, 1986).

3 Part 1 - Parameter investigation

3.1 Material and method

Based on literature in the area of four-point bending and packaging material, qualified guesses of which parameters that would affect the measurements were made. The speculation of which parameters could impact the result, made in this thesis, can be seen in the Ishikawa diagram below, Figure 6. The different parameters were investigated by creating experiments using the function DOE in minitab, to properly evaluate the impact of the parameters. Not all parameters were tested, as time and material were a constraint. Due to the construction and following of a DOE, systematic errors can be avoided due to the randomized testing sequence. The statistical impact of the different parameters can also be investigated due to the way the different tests in the DOE are set up.

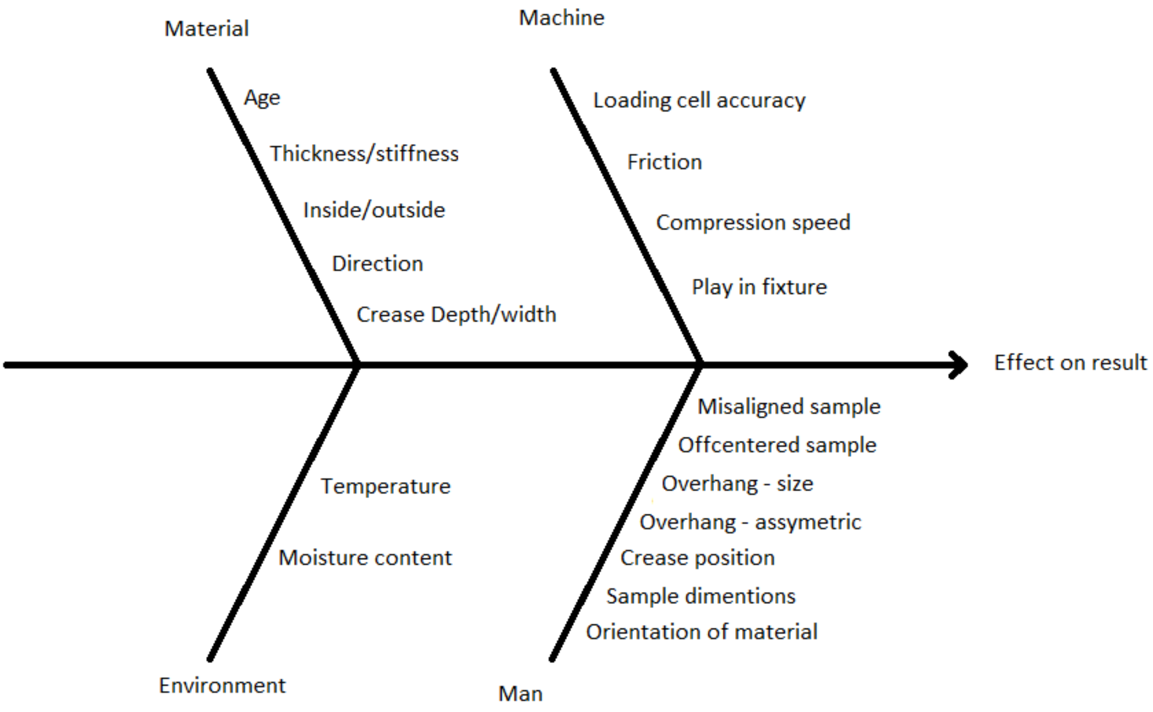

Figure 6 The different parameters identified that could impact the measurements.

The materials used in the different tests were chosen in a manner that several normal stiffnesses of paperboard used in the making of packages could be investigated. Available material was limited, whereas different tests used different kind of material from different distributors.

All tests performed in this study was done using a single aluminum fixture which can be seen in Figure 7. All tests have been performed using a Instron universal tester with a loadcell of 100 N. The Loadcell broke halfway through the experiments and another one was used to complete the tests. The specifications of the load cells can be found in Appendix 1. The starting point of the measurement was set by attaching the fixture to the measuring device. A sample was placed on the support pins and the loading pins were lowered until a change in force was detected. The loading pins were then raised 0,5 mm and the length and load were nulled. The recipe of the test has been to compress the samples with a speed of 10 mm/min until a change in force was discovered after which the speed was increased. The compression ended when one of two criteria were fulfilled, a compression of 8,5 mm or a registered load drop of 25% of the peak load registered if the peak was higher than 5 N. the registered data were compression distance and registered force. All data was modified to start at zero. This was done as the thickness of the samples varies, meaning that the initial distance until a load was registered would vary and the compression distance would be faulty. The modification was done using matlab. The data obtained were then analyzed using minitab.

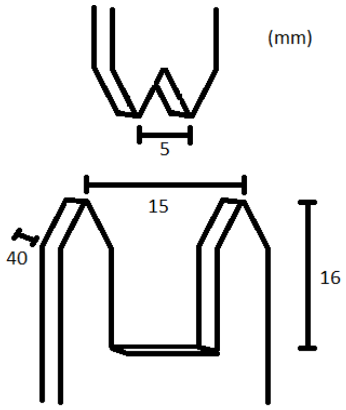

Figure 7 A schematic figure of the fixture used and its dimensions.

Metal, paperboard and packaging material have been investigated during the different tests. Metal has been used to investigate the importance of the position of uncreased material since the same sample can be reused multiple times, removing any variance in the material. Paperboard and packaging material has been used to validate the results of some of the metal tests and to investigate properties of creased material. The width of the metal samples was 25 mm with thicknesses varying between 0,04, 0,06 and 0,08 mm and the width of paperboard and packaging material was 38 mm.

All tests were designed using design of experiments two level full-factorial design with two factors.

Below in Figure 8 are a typical curve obtained during the measurement of the test.

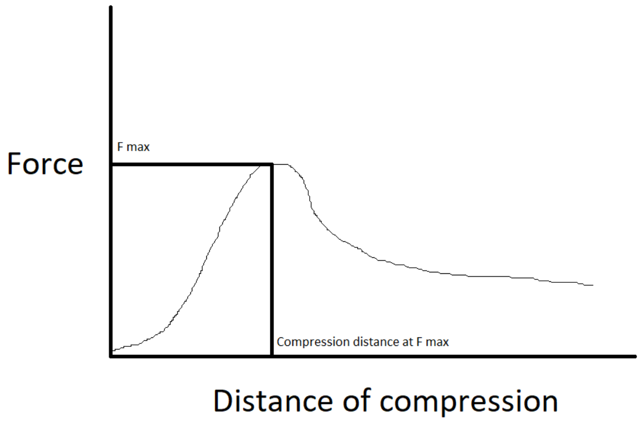

Figure 8 A general figure of how a curve obtained during the measurement could look like. F max and compression distance at F max are displayed in the figure as the peak value.

List of Designs of the experiments performed

Compression speed vs thickness of metal

Compression speed vs stiffness of paperboard

Play in loading pin vs thickness of metal

Misaligned and straight samples vs thickness of metal

Position under load cell vs thickness of metal

Asymmetrical overhang vs thickness of metal

Amount of overhang vs thickness of metal

Asymmetrical overhang vs stiffness of packaging material

Amount of overhang vs stiffness of packaging material

Position of crease vs packaging material direction Material 1

Position of crease vs packaging material direction Material 2

Position of crease vs packaging material direction Material 3

Folding direction vs stiffness of packaging material

These different tests will be further explained in detail below. The presented order is also the chronological order in which the tests were deducted. This means that findings in the early tests was used in later tests.

All data from the statistical analyses can be found in Appendix 2.

3.1.1 Compression speed vs thickness of metal

3.1.1.1 Aim and hypothesis

The aim of the experiment was to gain information of how the compression speed of the test influences the result of the test. A fast compression speed is wanted as it reduces the time to perform the measurements. No difference should be found as metal is not viscoelastic.

3.1.1.2 Settings and parameters

The test was done using metal samples to remove any variation of the material as the same samples can be used for all measurements since no plastic deformation happens.

The parameters varied was the compression speed and the thickness of the metal samples. The compression speed investigated were 20 mm/min, 60 mm/min and 100 mm/min. The thicknesses for the metal was 0,04 mm, 0,06 mm and 0,08 mm. The metal samples had the dimension 25*40 mm. This test was performed on the first measuring device.

The design of the experiment can be seen in Table 1 below.

Table 1 The design of the experiment showing the randomized run order and the different settings of the parameters.

StdOrder	RunOrder	CenterPt	Blocks	Compression speed (mm/min)	Thickness (mm)
11	1	0	1	60	0,06
5	2	1	1	20	0,04
7	3	1	1	20	0,08
2	4	1	1	100	0,04
8	5	1	1	100	0,08
1	6	1	1	20	0,04
3	7	1	1	20	0,08
4	8	1	1	100	0,08
10	9	0	1	60	0,06
6	10	1	1	100	0,04
9	11	0	1	60	0,06

3.1.1.3 Result

The results of the measurement showed that the sample thickness significantly affected the result while the compression speed did not. The Pareto chart for the test can be seen in Figure 9 below.

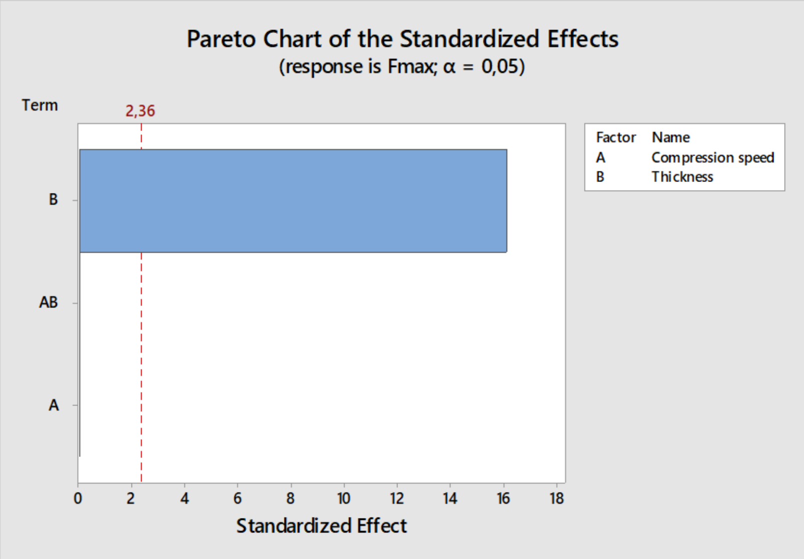

Figure 9 A pareto chart showing the impact of the different factors. Factor B, the thickness, is significant as it crosses the red line.

Figure 10 below depicts the means of the different test parameters.

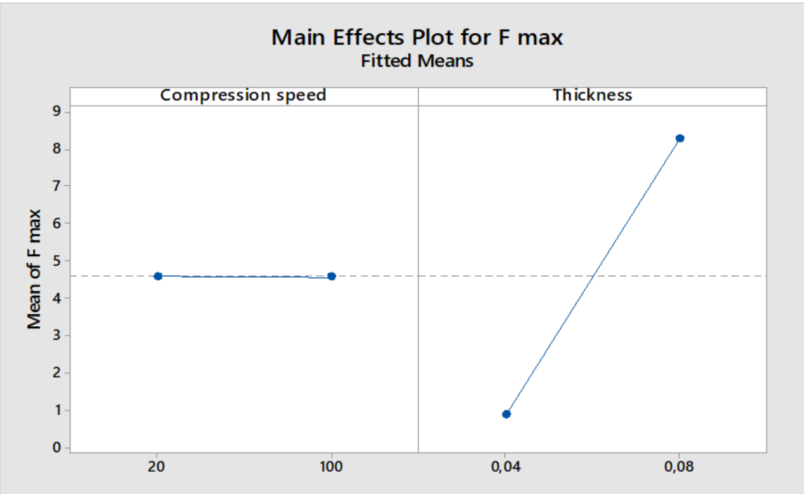

Figure 10 The main effects plot for the test shows the mean result of each parameter.

The model summary of the trial can be seen in Table 2. If only the significant factors were accounted for, the R-sq(pred) increased to 96,50%.

Table 2 Model summary for compression speed of metal.

S	R-sq	R-sq(adj)	PRESS	R-sq(pred)
0,650427	97,36%	96,23%	5,45250	95,14%

3.1.2 Compression speed vs stiffness of paperboard

3.1.2.1 Aim and hypothesis

The aim of the experiment was to investigate if the different stiffnesses for paperboard behaved the same way as the metal samples did or if the properties of the paperboard would cause a different pattern as paperboard is viscoelastic.

3.1.2.2 Settings and parameters

The test was done using paperboard samples with the dimensions 38*40 mm and were deformed in the MD direction. The material was Duplex with different stiffnesses. The clay coat was facing downwards to simulate the normal bending direction.

The parameters varied was the compression speed and the stiffness of the paperboard samples. The compression speed investigated were 20 mm/min, 60 mm/min and 100 mm/min. The stiffnesses for the paperboard was 80 mN, 150 mN and 260 mN. This test was performed on the first measuring device. The actual centerpoint was 150 mN but no material of that stiffness was present, resulting in 170 mN being used instead.

The design of the experiment can be seen in Table 3 below.

Table 3 The design of the experiment showing the randomized run order and the different settings of the parameters.

StdOrder	RunOrder	CenterPt	Blocks	Compression speed (mm/min)	Stiffness (mN)
11	1	0	1	60	150
9	2	1	1	100	260
2	3	0	1	60	80
7	4	1	1	20	260
5	5	0	1	60	150
3	6	1	1	100	80
6	7	1	1	100	150
10	8	0	1	60	80
1	9	1	1	20	80
8	10	0	1	60	260
4	11	1	1	20	150
12	12	0	1	60	260

3.1.2.3 Result

The results of the measurement showed that the sample stiffness significantly affected the result while the compression speed did not. The Pareto chart for the test can be seen in Figure 11 below.

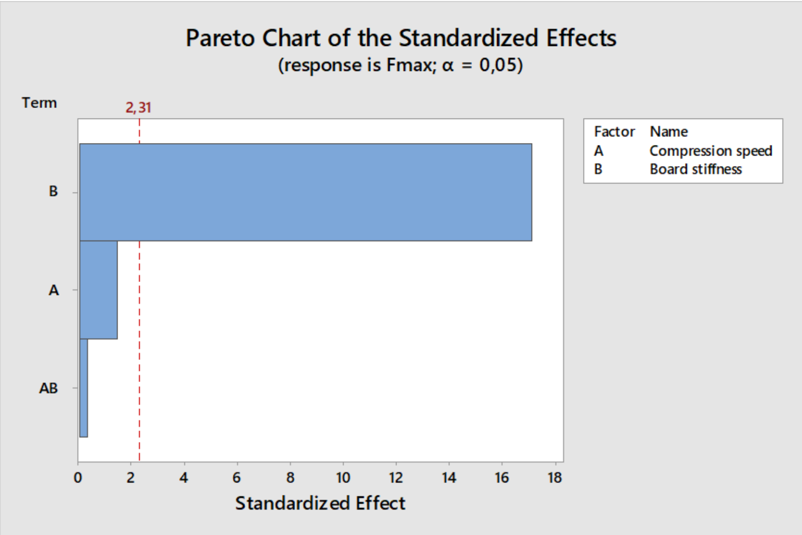

Figure 11 A pareto chart showing the impact of the different factors. Factor B, the stiffness, is significant as it crosses the red line.

Figure 12 below depicts the means of the different test parameters.

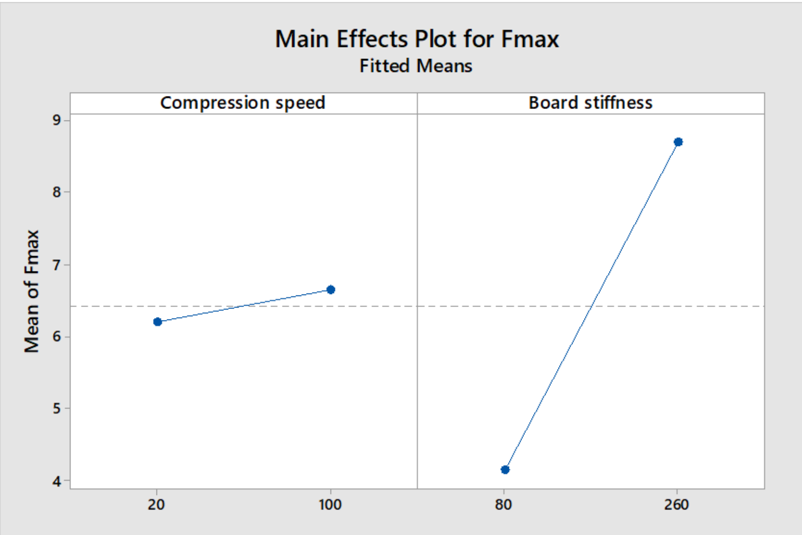

Figure 12 The main effects plot for the test shows the mean result of each parameter

The model summary of the trial can be seen in Table 4. If only the significant factors were accounted for, the R-sq(pred) increased to 95,44%.

Table 4 Model summary of compression speed of paperboard.

S	R-sq	R-sq(adj)	PRESS	R-sq(pred)
0,379207	97,35%	96,35%	2,16276	95,02%

3.1.3 Play in loading pin vs thickness of metal

3.1.3.1 Aim and hypothesis

As the loading fixture had some play in the Universal tester, the aim of this study was to investigate if this play would significantly affect the measured value. The play is small and this study will most likely not have a significant impact on the measurement.

3.1.3.2 Settings and parameters

The test was performed using metal samples to eliminate any variance in the material. The parameters varied in the test was the position of the loading pins and the thickness of the samples. The samples had the dimension 25*40 mm. the thicknesses of the samples were 0,04 mm, 0,06 mm and 0,08 mm. A compression speed of 100 mm/min was used throughout the test. The different positions were achieved by manually twisting the load pin fixture clockwise until it reached the maximum misalignment. This position was compared to the centered one. The test setup can be seen in Figure 13 below. This test was performed on the first measuring device.

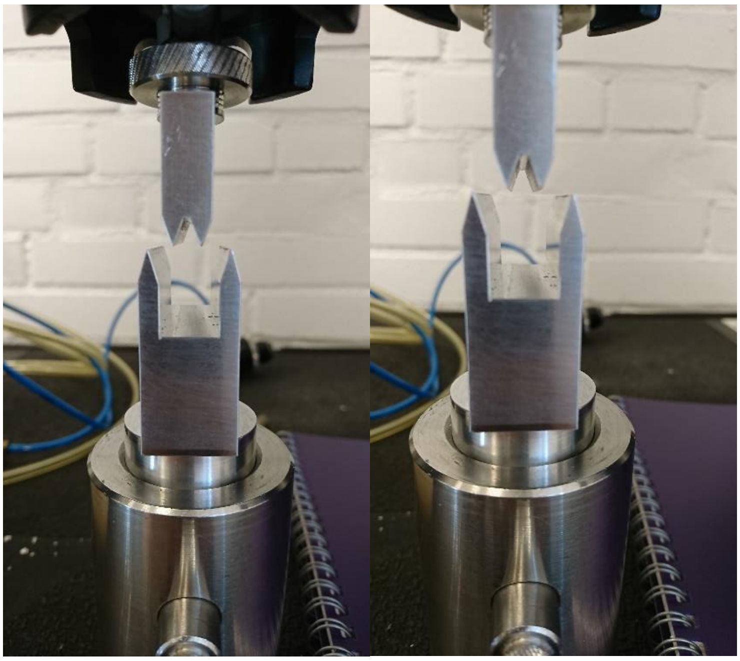

Figure 13 The play in the loading pins. The figure to the left shows the most angled position and the figure to the right shows the most centered position.

The design of the experiment can be seen in Table 5 below.

Table 5 The design of the experiment showing the randomized run order and the different settings of the parameters.

StdOrder	RunOrder	CenterPt	Blocks	Thickness (mm)	Position
7	1	0	1	0,06	Left
1	2	1	1	0,04	Left
2	3	1	1	0,08	Left
3	4	1	1	0,04	Center
5	5	0	1	0,06	Left
8	6	0	1	0,06	Center
6	7	0	1	0,06	Center
4	8	1	1	0,08	Center

3.1.3.3 Results

The results showed that the thickness of the sample was the only thing that affected the outcome of the measurement and that the position of the loading fixture did not play a significant role. The Pareto chart for the test can be seen in Figure 14 below.

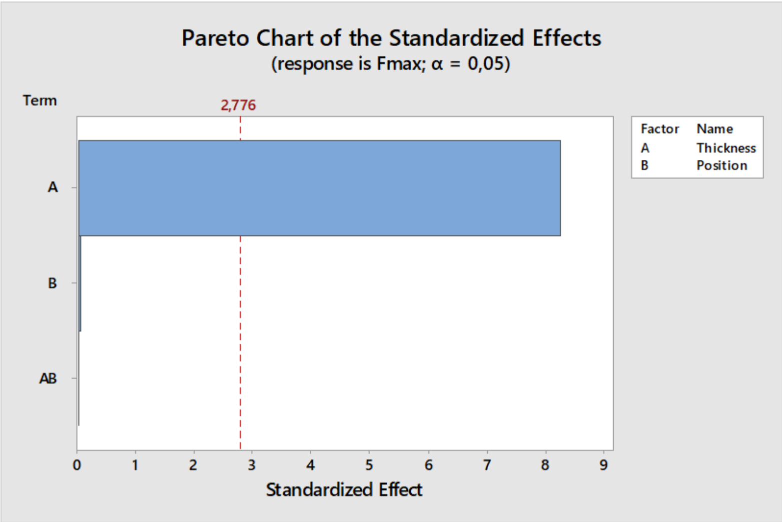

Figure 14 A pareto chart showing the impact of the different factors. Factor A, the thickness, is significant as it crosses the red line.

Figure 15 below depicts the means of the different test parameters.

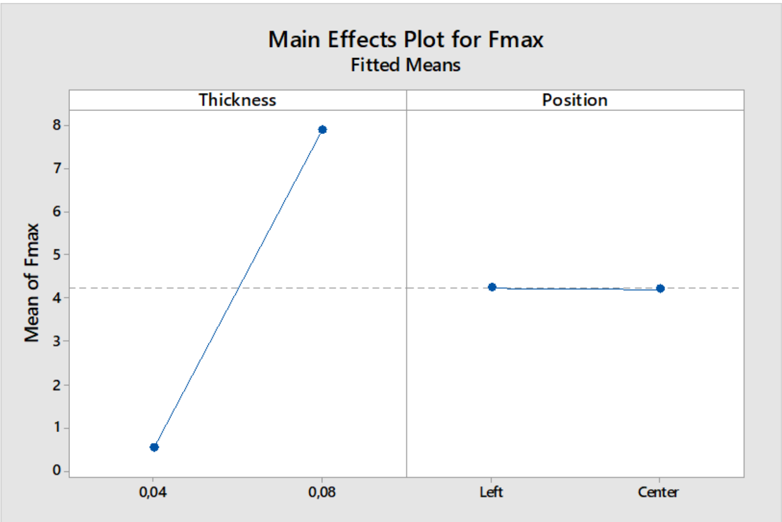

Figure 15 The main effects plot for the test shows the mean result of each parameter.

The model summary of the trial can be seen in Table 6. If only the significant factors were accounted for, the R-sq(pred) increased to 89,31%.

Table 6 Model summary of play in loading pins.

S	R-sq	R-sq(adj)	PRESS	R-sq(pred)
0,889347	94,48%	90,33%	28,1163	50,91%

3.1.4 Misaligned and straight samples vs thickness of metal

3.1.4.1 Aim and hypothesis

The aim of the test was to investigate how the positioning of the sample in the test rig would affect the measured value. This test will give information about the importance of the placement of the sample if the material cannot be cut into 38 mm wide strips, e.g. if there is an interfering crease. The angled sample should have slightly higher max force but not necessarily significant as the sample will appear wider than it is.

3.1.4.2 Settings and parameters

The test was performed using metal samples to eliminate any variance in the material. The parameters varied in the test was the thickness and the position of the sample. The samples had the dimensions 25*40 mm. A compression speed of 100 mm/min was used throughout the test. The thicknesses of the samples were 0,04 mm, 0,06 mm and 0,08 mm. The samples were placed centered in the test rig and angled, the positions can be seen in Figure 16 below. This test was performed on the first measuring device.

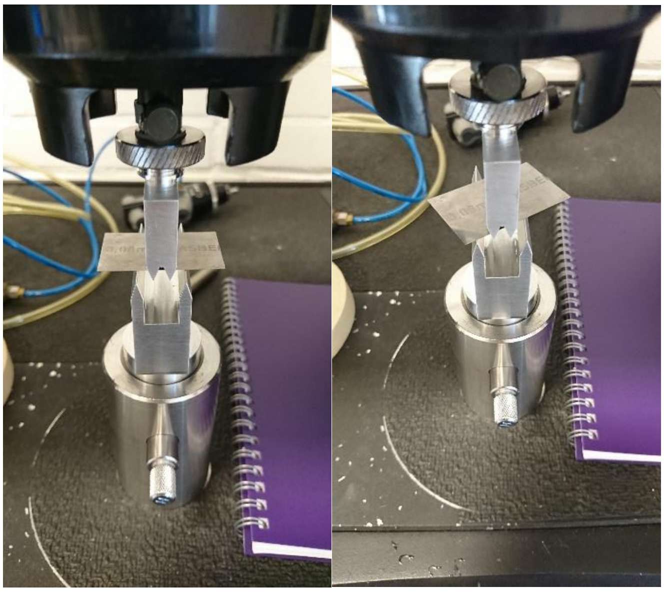

Figure 16 The picture to the left shows the test setup with the sample straight in the fixture and the picture to the right shows the test setup with an angled sample in the fixture.

The design of the experiment can be seen in Table 7 below.

Table 7 The design of the experiment showing the randomized run order and the different settings of the parameters.

StdOrder	RunOrder	CenterPt	Blocks	Thickness (mm)	Position
7	1	0	1	0,06	Angled
6	2	0	1	0,06	Straight
8	3	0	1	0,06	Straight
2	4	1	1	0,08	Angled
1	5	1	1	0,04	Angled
3	6	1	1	0,04	Straight
4	7	1	1	0,08	Straight
5	8	0	1	0,06	Angled

3.1.4.3 Result

The data shows that the thickness significantly affected the outcome of the measurement while the position did not. The Pareto chart for the test can be seen in Figure 17 below.

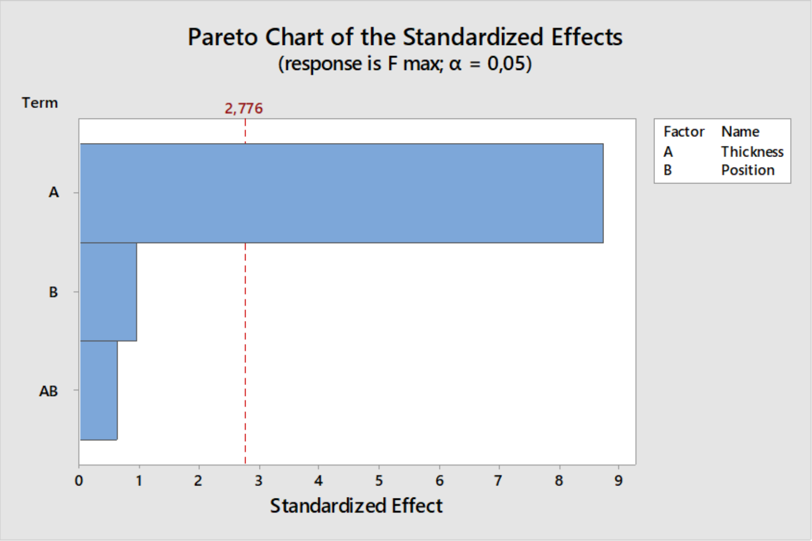

Figure 17 A pareto chart showing the impact of the different factors. Factor A, the thickness, is significant as it crosses the red line.

Figure 18 below depicts the means of the different test parameters.

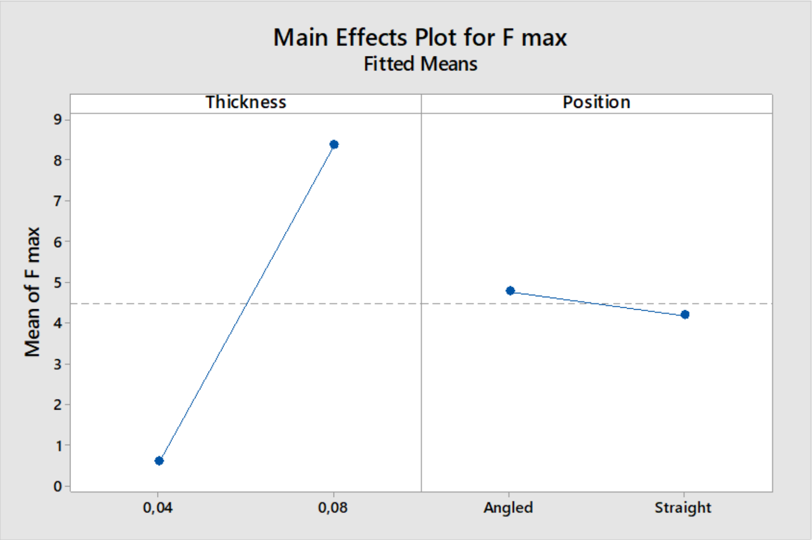

Figure 18 The main effects plot for the test shows the mean result of each parameter.

The model summary of the trial can be seen in Table 8. If only the significant factors were accounted for, the R-sq(pred) increased to 86,86%.

Table 8 Model summary of misaligned or straight sample.

S	R-sq	R-sq(adj)	PRESS	R-sq(pred)
0,888065	95,11%	91,45%	28,0401	56,55%

3.1.5 Position under load cell vs thickness of metal

3.1.5.1 Aim and hypothesis

The aim of the test was to gain knowledge of how the positioning of the sample under the loading cell affected the outcome of the measurement. The result would give information of how the sample should be placed if the material cannot be cut into strips with a width of 38 mm, e.g. due to an interfering crease. The position should not significantly affect the outcome as the fixture is quite rigid and the shear force introduced should be low due to a rather small fixture.

3.1.5.2 Settings and parameters

The test was performed using metal samples to eliminate any variance in the material. The parameters varied in the test was the thickness and the position of the sample. The samples had the dimensions 25*40 mm. A compression speed of 100 mm/min was used throughout the test. The thicknesses of the samples were 0,04 mm, 0,06 mm and 0,08 mm. The samples were placed centered and off centered in the fixture. The positions can be seen in Figure 19 below.

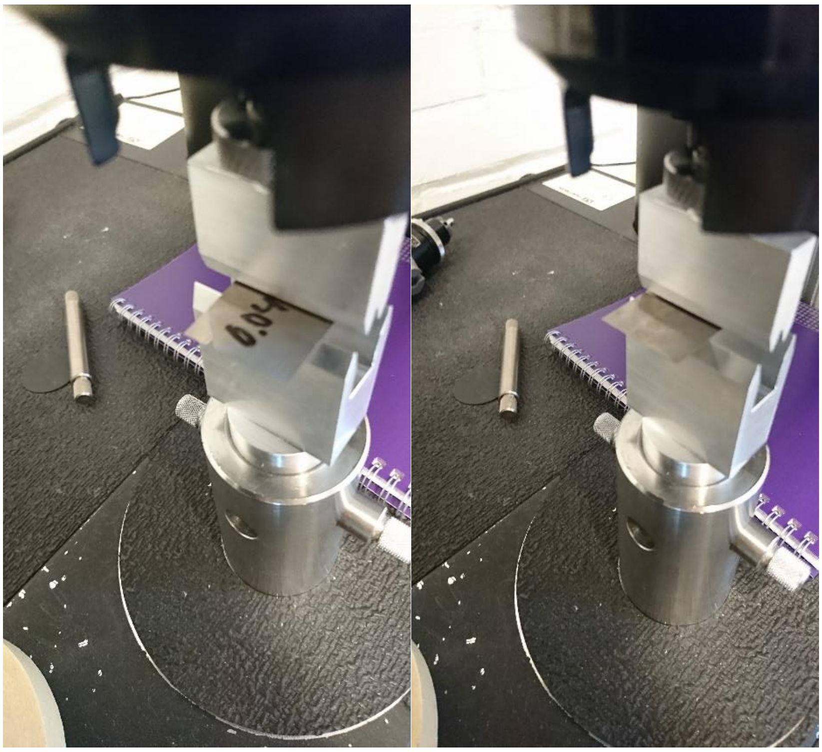

Figure 19 The picture to the left shows the centered position of the sample and the picture to the right shows the off centered sample position.

The design of the experiment can be seen in Table 9 below.

Table 9 The design of the experiment showing the randomized run order and the different settings of the parameters.

StdOrder	RunOrder	CenterPt	Blocks	Thickness (mm)	Position
8	1	0	1	0,06	Centered
4	2	1	1	0,08	Centered
5	3	0	1	0,06	Off center
3	4	1	1	0,04	Centered
1	5	1	1	0,04	Off center
2	6	1	1	0,08	Off center
6	7	0	1	0,06	Centered
7	8	0	1	0,06	Off center

3.1.5.3 Results

The results showed that the thickness significantly impacted the outcome of the measurement, but the position did not. The Pareto chart for the test can be seen in Figure 20 below.

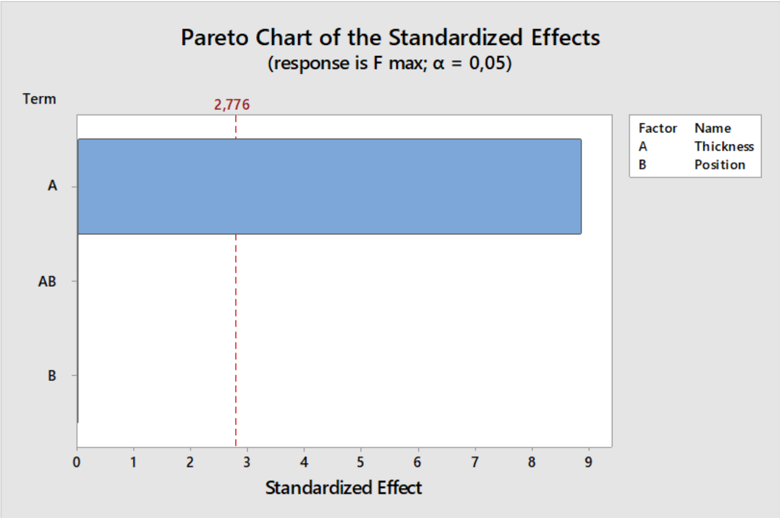

Figure 20 A pareto chart showing the impact of the different factors. Factor A, the thickness, is significant as it crosses the red line.

Figure 21 depicts below the means of the different test parameters.

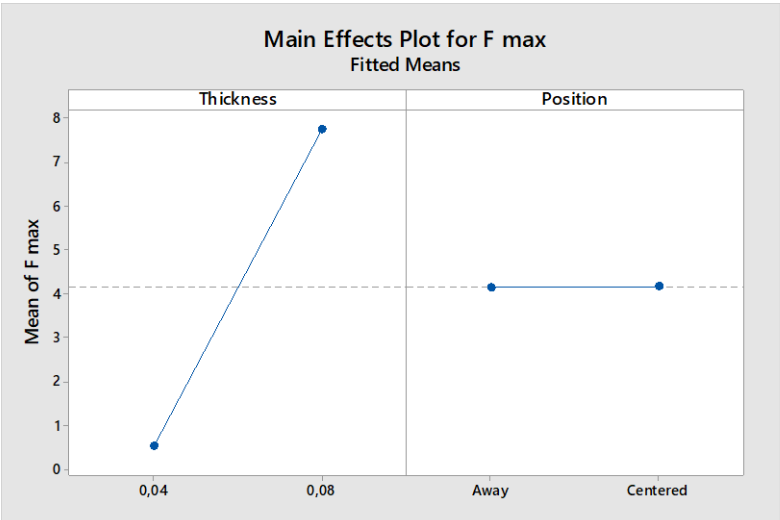

Figure 21 The main effects plot for the test shows the mean result of each parameter.

The model summary of the trial can be seen in Table 10. If only the significant factors were accounted for, the R-sq(pred) increased to 95,44%.

Table 10 Model summary of position under load cell.

S	R-sq	R-sq(adj)	PRESS	R-sq(pred)
0,813653	95,17%	91,54%	23,5379	90,65%

3.1.6 Asymmetrical overhang vs thickness of metal

3.1.6.1 Aim and hypothesis

The aim of the experiment was to gain knowledge of how the position, regarding asymmetry in overhang, would affect the measured results. The result would give useful information regarding how to prepare the samples in the final test procedure. The outcome could come to show that there is a statistical difference due to introduction of new forces.

3.1.6.2 Settings and parameters

The test was performed using metal samples to eliminate any variance in the material. The parameters varied in the test was the thickness and the position of the sample. The samples had the dimensions 25*70 mm. A compression speed of 100 mm/min was used throughout the test. The thicknesses of the samples were 0,04 mm, 0,06 mm and 0,08 mm. The samples were placed centered and off centered in the rig. The two positions can be seen in Figure 22 below. This test was performed on the second measuring device.

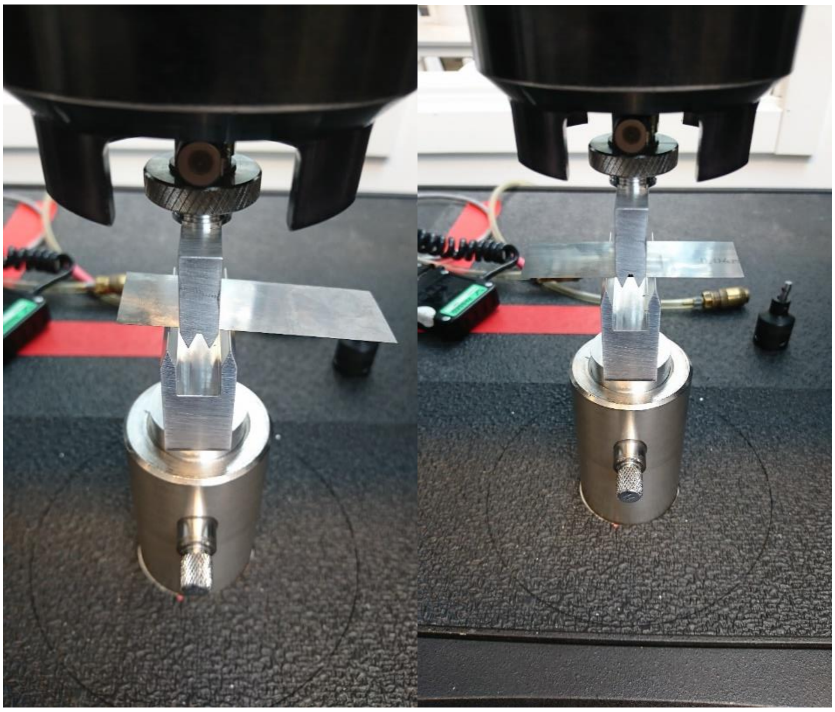

Figure 22 The picture to the left shows the setup with an uncentred metal sample and the picture to the right shows the setup with a centered sample.

The design of the experiment can be seen in Table 11 below.

Table 11 The design of the experiment showing the randomized run order and the different settings of the parameters.

StdOrder	RunOrder	CenterPt	Blocks	Thickness (mm)	Overhang position
6	1	0	1	0,06	Offcenter
8	2	0	1	0,06	Offcenter
7	3	0	1	0,06	Center
4	4	1	1	0,08	Offcenter
2	5	1	1	0,08	Center
1	6	1	1	0,04	Center
5	7	0	1	0,06	Center
3	8	1	1	0,04	Offcenter

3.1.6.3 Results

The results showed that the thickness significantly impacted the outcome of the measurement, but the position did not. The Pareto chart for the test can be seen in Figure 23 below.

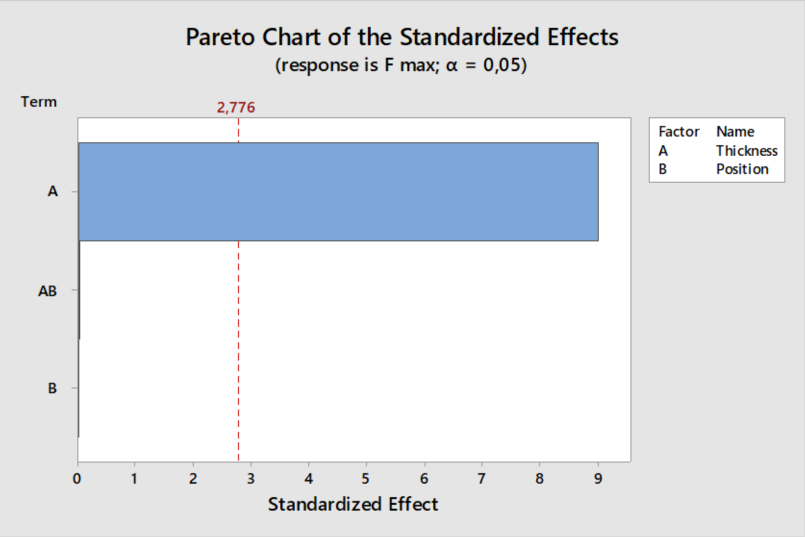

Figure 23 A pareto chart showing the impact of the different factors. Factor A, the thickness, is significant as it crosses the red line.

Figure 24 depicts below the means of the different test parameters.

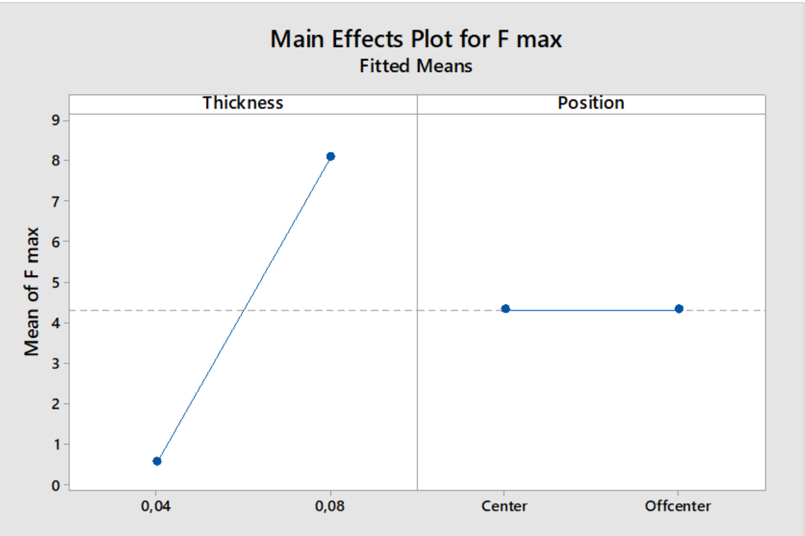

Figure 24 The main effects plot for the test shows the mean result of each parameter.

The model summary of the trial can be seen in Table 12. If only the significant factors were accounted for, the R-sq(pred) increased to 90,95%.

Table 12 Model summary of overhang position for metal.

S	R-sq	R-sq(adj)	PRESS	R-sq(pred)
0,832962	95,32%	91,81%	24,6208	58,48%

3.1.7 Amount of overhang vs thickness of metal

3.1.7.1 Aim and hypothesis

The aim of the experiment was to gain knowledge regarding the effect of the amount of overhang on the measured value. The knowledge would be used to determine how the final measuring procedure should be carried out regarding how the samples should be prepared. The effect of the overhang could come to show that there is a statistical difference of the lengths due to larger moving parts presenting higher counter force.

3.1.7.2 Settings and parameters

The test was performed using metal samples to eliminate any variance in the material. The parameters varied in the test was the thickness and the size of the sample. The samples had the dimensions 25*40 mm, 25*70 mm and 25*100 mm. A compression speed of 100 mm/min was used throughout the test. The thicknesses of the samples were 0,04 mm, 0,06 mm and 0,08 mm. The samples were placed centered in the rig. This test was performed on the second measuring device. Figure 25 displays how the test setup looked like, much overhang to the left and little to the right.

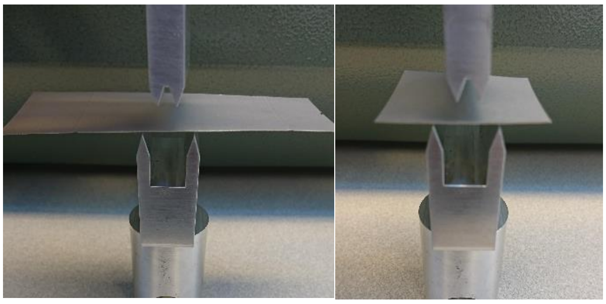

Figure 25 The different amounts of overhang, the left picture shows a 100 mm sample and the right one shows a 40 mm sample.

The design of the experiment can be seen in Table 13 below.

Table 13 The design of the experiment showing the randomized run order and the different settings of the parameters.

StdOrder	RunOrder	CenterPt	Blocks	Thickness (mm)	Sample length (mm)
3	1	1	1	0,04	100
6	2	0	1	0,06	70
5	3	0	1	0,06	70
7	4	0	1	0,06	70
1	5	1	1	0,04	40
4	6	1	1	0,08	100
2	7	1	1	0,08	40

3.1.7.3 Result

The thickness showed a significant effect on the measurement, but the length of the sample did not. The Pareto chart for the test can be seen in Figure 26 below.

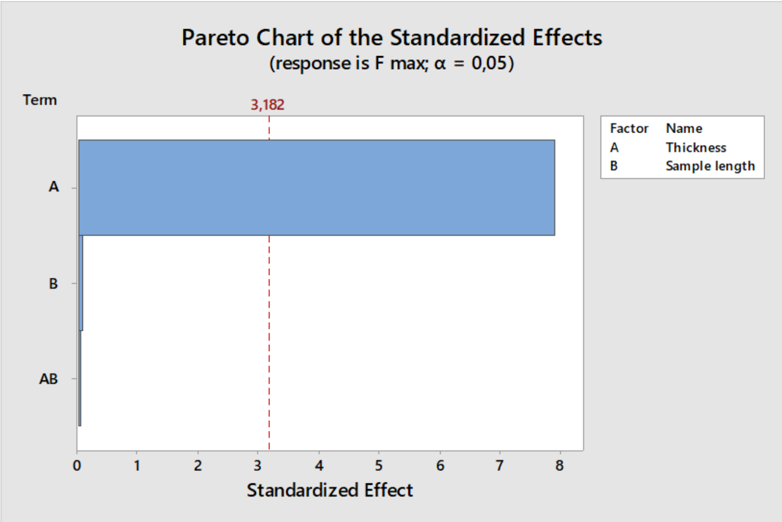

Figure 26 A pareto chart showing the impact of the different factors. Factor A, the thickness, is significant as it crosses the red line.

Figure 27 depicts below the means of the different test parameters.

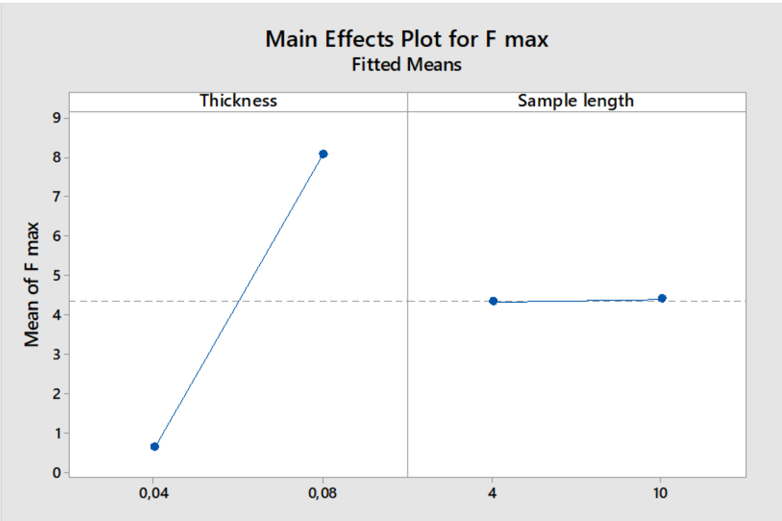

Figure 27 The main effects plot for the test shows the mean result of each parameter.

The model summary of the trial can be seen in Table 14. If only the significant factors were accounted for, the R-sq(pred) increased to 91,04%.

Table 14 Model summary of amount of overhang for metal.

S	R-sq	R-sq(adj)	PRESS	R-sq(pred)
0,943135	95,41%	90,81%	101,673	0,00%

3.1.8 Asymmetrical overhang vs stiffness of paperboard

3.1.8.1 Aim and hypothesis

The aim with this test was to confirm that paperboard does not differ from the metal samples in how it behaves when folded with asymmetric overhang. As the metal did not differ, neither should this.

3.1.8.2 Settings and parameters

Paperboard was used to verify that the data obtained from the same test using metal pieces can be used since paper has different properties and is anisomeric and viscoelastic. The paperboard used was bleached material.

The parameters varied in the test was the stiffness of the paperboard and the position of the sample. The samples had the dimensions 38*70 mm. A compression speed of 100 mm/min was used throughout the test. The stiffnesses tested were 80 mN, 150 mN and 260 mN. The samples were placed centered and off centered in the rig. The two positions can be seen in Figure 22 (same as the metal one). To reduce the effect of the variance of the material, three samples was used in each measurement and the mean max force was calculated. The samples were prepared in a way so that the fold was in the MD direction. the clay coat was facing down during the measurements. The samples had been conditioned in 22,5 C 50 RH for two years. This test was performed on the second measuring device.

The design of the experiment can be seen in Table 15 below. A is the position of the sample and B is the stiffness of the sample.

Table 15 The design of the experiment showing the randomized run order and the different settings of the parameters.

StdOrder	RunOrder	CenterPt	Blocks	Overhang position	Stiffness
2	1	1	1	Offcenter	80
6	2	0	1	Offcenter	150
7	3	0	1	Center	150
1	4	1	1	Center	80
8	5	0	1	Offcenter	150
4	6	1	1	Offcenter	260
3	7	1	1	Center	260
5	8	0	1	Center	150

3.1.8.3 Results

The stiffness showed a significant effect on the measurement but the position of the sample did not. The Pareto chart for the test can be seen in Figure 28 below.

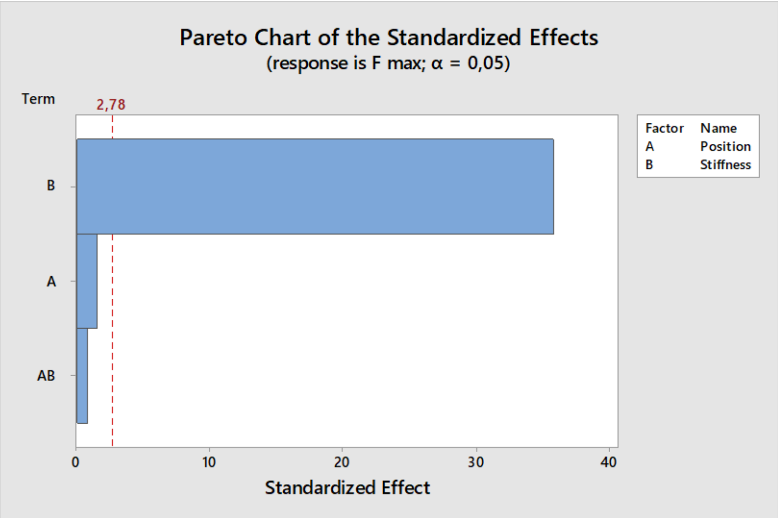

Figure 28 A pareto chart showing the impact of the different factors. Factor B, the stiffness, is significant as it crosses the red line.

Figure 29 depicts below the means of the different test parameters.

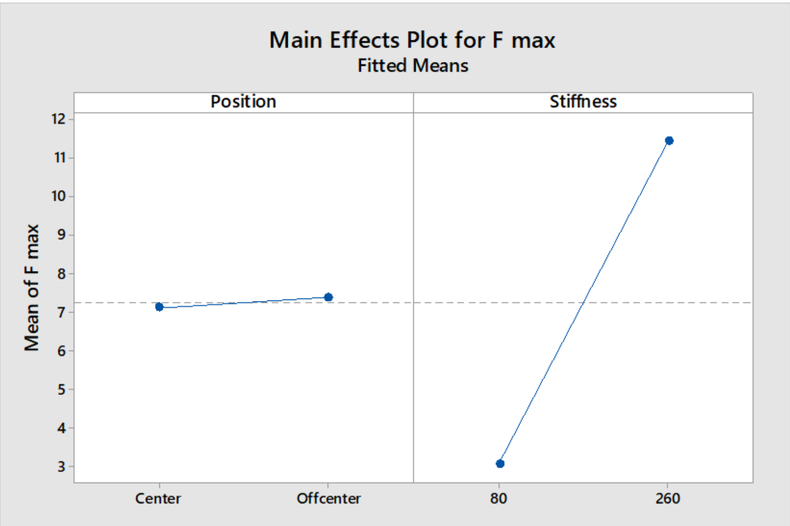

Figure 29 The main effects plot for the test shows the mean result of each parameter.

The model summary of the trial can be seen in Table 16. If only the significant factors were accounted for, the R-sq(pred) increased to 98,78%.

Table 16 Model summary of position of overhang for paperboard.

S	R-sq	R-sq(adj)	PRESS	R-sq(pred)
0,233726	99,69%	99,46%	1,90426	97,29%

3.1.9 Amount of overhang vs stiffness of paperboard

3.1.9.1 Aim and hypothesis

The aim with this test was to confirm that paperboard does not differ from the metal samples in how it behaves when folded with different amounts of overhang. As the metal did not differ, neither should this.

3.1.9.2 Settings and parameters

Paperboard was used to verify that the data obtained from the same test using metal pieces can be used since paper has different properties and is viscoelastic and anisotropic. The paperboard used was bleached material.

The parameters varied in the test was the size of the sample and the stiffness of the sample. The samples had the dimensions 38*4 mm, 38*70 mm and 38*100 mm. A compression speed of 100 mm/min was used throughout the test. The stiffnesses tested were 80 mN, 150 mN and 260 mN. The samples were placed centered in the rig. To reduce the effect of the variance of the material, three samples was used in each measurement and the mean max force was calculated. The samples were prepared in a way so that the fold was in the MD direction. the clay coat was facing down during the measurements. The samples had been conditioned in 22,5 C 50 RH for two years. This test was performed on the second measuring device.

The design of the experiment can be seen in Table 17 below.

Table 17 The design of the experiment showing the randomized run order and the different settings of the parameters.

StdOrder	RunOrder	CenterPt	Blocks	Sample length (cm)	Stiffness (mN)
7	1	0	1	7	150
5	2	0	1	7	150
4	3	1	1	10	260
3	4	1	1	4	260
6	5	0	1	7	150
2	6	1	1	10	80
1	7	1	1	4	80

3.1.9.3 Results

The stiffness showed a significant effect on the measurement but the length of the sample did not. The Pareto chart for the test can be seen in Figure 30 below.

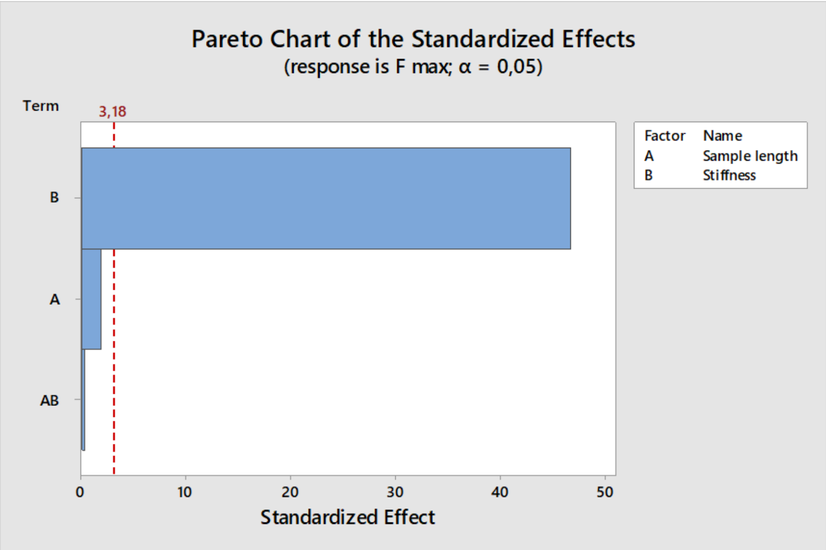

Figure 30 A pareto chart showing the impact of the different factors. Factor B, the stiffness, is significant as it crosses the red line.

Figure 31 depicts below the means of the different test parameters.

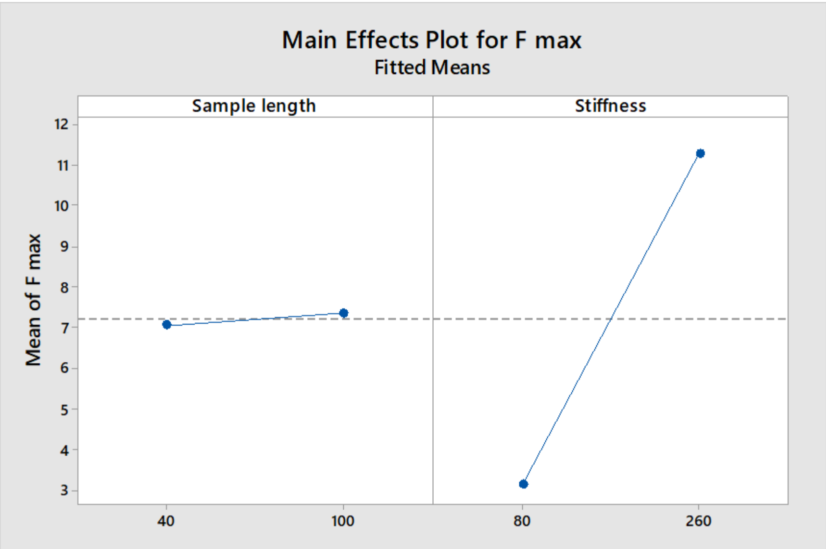

Figure 31 The main effects plot for the test shows the mean result of each parameter.

The model summary of the trial can be seen in Table 18. If only the significant factors were accounted for, the R-sq(pred) increased to 99,33%.

Table 18 Model summary of amount of overhang for paperboard.

S	R-sq	R-sq(adj)	PRESS	R-sq(pred)
0,173578	99,86%	99,73%	2,84200	95,70%

3.1.10 Position of crease vs packaging material direction

3.1.10.1 Aim and hypothesis

The aim of the test was to investigate how the position of the crease between the loading pins and the direction of the crease (MD/CD) would affect the measured value. As the weakest point no longer necessarily is located between the loading pins, but rather beneath one of them, this position could behave more like an uncreased sample. This could lead to a statistical difference.

3.1.10.2 Settings and parameters

Three different materials were investigated, two which had a stiffness of 80 mN and one with a stiffness of 260 mN.

The parameters varied in the test was the position of the crease between the loading pins and the direction of the crease (MD/CD). The different positions were 0% offset (centered sample), 50% offset and 100% offset (crease directly under the loading pin), see Figure 32. These measures were done for both MD and CD. A compression speed of 100 mm/min was used throughout the test. The samples had the dimensions 38*40 mm with the crease centered. To reduce the effect of the variance of the material, five samples was used in each measurement and the mean max force was calculated. The test was performed with the inside of the packaging material facing up. The samples were conditioned in 23 C 50 RH for six days. These tests were performed on the second measuring device.

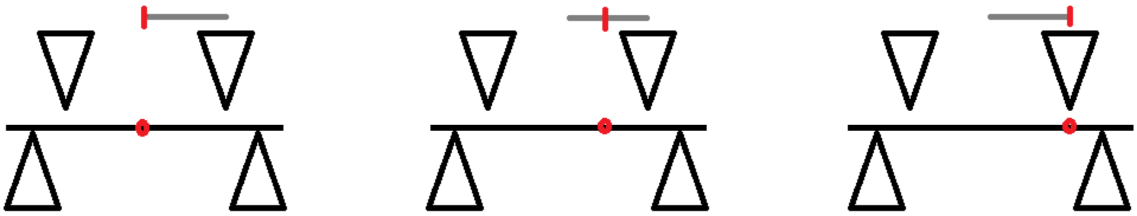

Figure 32 The three investigated crease positions. The first fixture shows the crease at 0% offset (centered). The second fixture shows the crease at 50 % offset (halfway to the edge from the center). The third fixture shows the crease at 100% offset (directly beneath the loading pin).

The design of the experiments can be seen in Table 19-21 below.

Material 1

Table 19 The design of the experiment showing the randomized run order and the different settings of the parameters.

StdOrder	RunOrder	PtType	Blocks	Position	Direction
12	1	1	1	100%	CD
4	2	1	1	50%	CD
5	3	1	1	100%	MD
8	4	1	1	0%	CD
10	5	1	1	50%	CD
7	6	1	1	0%	MD
3	7	1	1	50%	MD
11	8	1	1	100%	MD
6	9	1	1	100%	CD
9	10	1	1	50%	MD
2	11	1	1	0%	CD
1	12	1	1	0%	MD

Material 2

Table 20 The design of the experiment showing the randomized run order and the different settings of the parameters.

StdOrder	RunOrder	PtType	Blocks	Position	Direction
4	1	1	1	50%	CD
2	2	1	1	0%	CD
10	3	1	1	50%	CD
3	4	1	1	50%	MD
11	5	1	1	100%	MD
5	6	1	1	100%	MD
7	7	1	1	0%	MD
12	8	1	1	100%	CD
8	9	1	1	0%	CD
6	10	1	1	100%	CD
1	11	1	1	0%	MD
9	12	1	1	50%	MD

Material 3

Table 21 The design of the experiment showing the randomized run order and the different settings of the parameters.

StdOrder	RunOrder	PtType	Blocks	Position	Direction
5	1	1	1	100%	MD
11	2	1	1	100%	MD
2	3	1	1	0%	CD
4	4	1	1	50%	CD
3	5	1	1	50%	MD
8	6	1	1	0%	CD
10	7	1	1	50%	CD
9	8	1	1	50%	MD
12	9	1	1	100%	CD
6	10	1	1	100%	CD
1	11	1	1	0%	MD
7	12	1	1	0%	MD

3.1.10.3 Result

3.1.10.3.1 Material 1

The Direction showed a significant effect on the measurement, but the position of the crease did not. The Pareto chart for the test can be seen in Figure 33 below.

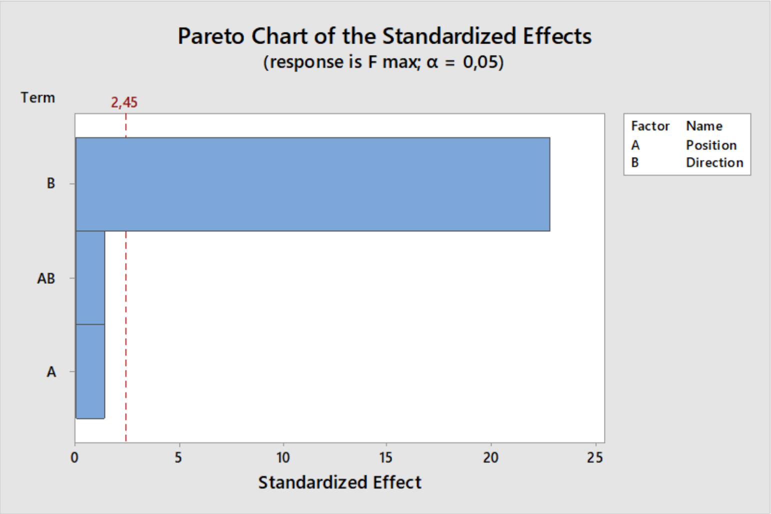

Figure 33 A pareto chart showing the impact of the different factors on material 1. Factor B, the direction, is significant as it crosses the red line.

The model summary of the trial can be seen in Table 22. If only the significant factors were accounted for, the R-sq(pred) increased to 96,22%.

Table 22 Model summary of crease position for material 1.

S	R-sq	R-sq(adj)	PRESS	R-sq(pred)
0,175775	98,88%	97,94%	0,741522	95,51%

Figure 34 depicts below the means of the different test parameters.

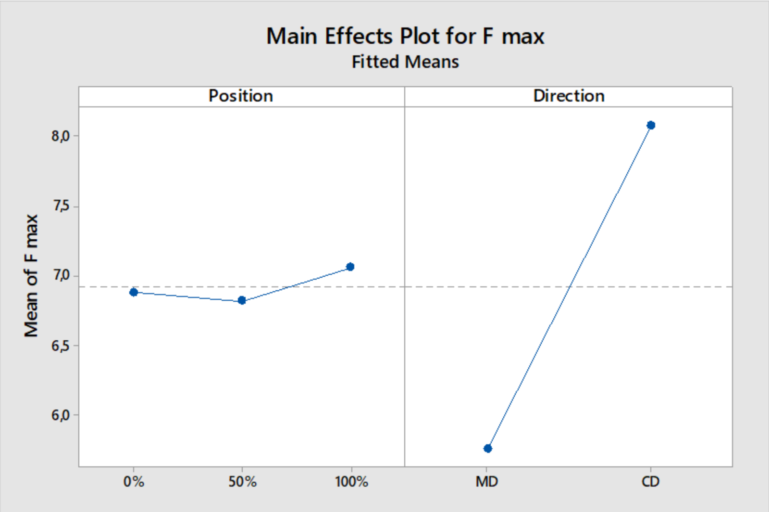

Figure 34 The main effects plot for the test shows the mean result of each parameter for material 1.

The compression distances to the maximum registered force of MD and CD at the three positions can be seen in Figure 35 below.

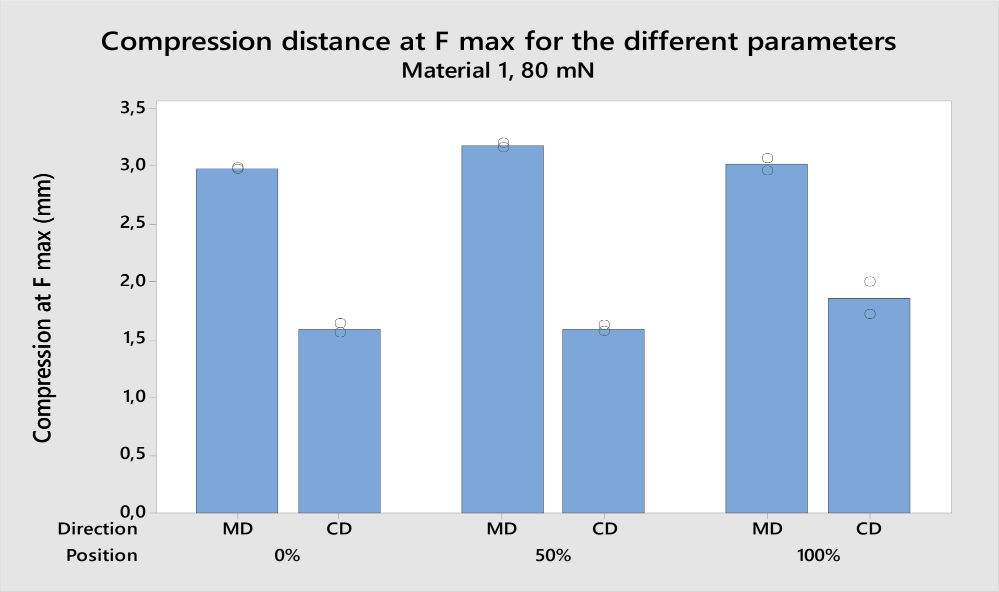

Figure 35 The compressions distance at the maximum registered force for the different positions for material 1. Each direction and position are measured twice.

Figure 36 below shows the pareto chart for factors affecting the compression distance. It can be seen that the direction significantly affects the compression distance.

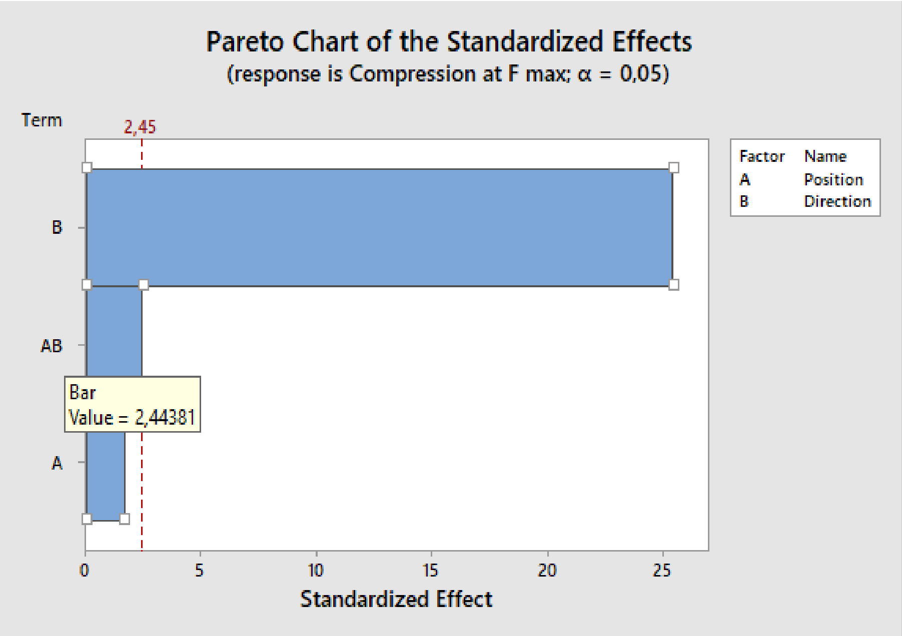

Figure 36 Pareto chart showing the impact of the different factors on the compression distance for material 1. Factor B, the Direction is significant as it crosses the red line.

3.1.10.3.2 Material 2

The Direction showed a significant effect on the measurement, but the position of the crease did not. The Pareto chart for the test can be seen in Figure 37 below.

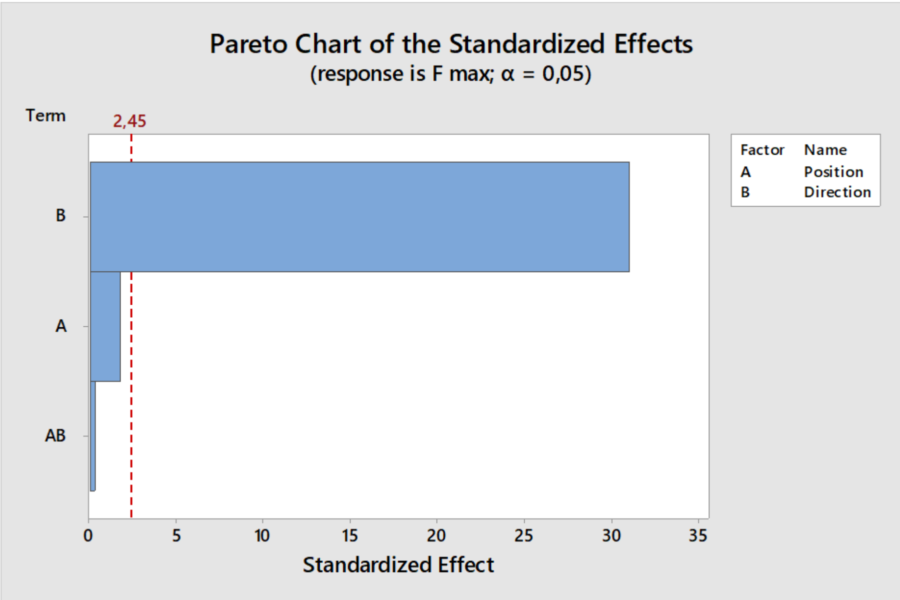

Figure 37 A pareto chart showing the impact of the different factors of material 2. Factor B, the direction, is significant as it crosses the red line.

The model summary of the trial can be seen in Table 23. If only the significant factors were accounted for, the R-sq(pred) increased to 98,14 %.

Table 23 Model summary of crease position for material 2.

S	R-sq	R-sq(adj)	PRESS	R-sq(pred)
0,143101	99,39%	98,87%	0,491468	97,54%

Figure 38 depicts below the means of the different test parameters.

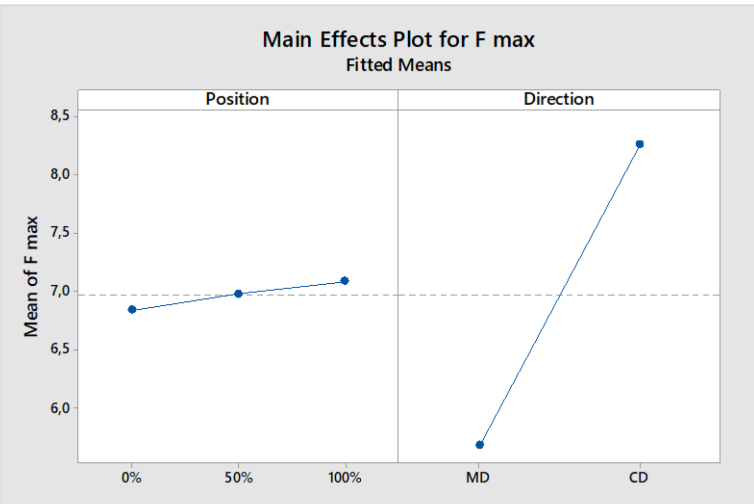

Figure 38 The main effects plot for the test shows the mean result of each parameter for material 2.

The compression distances to the maximum registered force of MD and CD at the three positions can be seen in Figure 39 below.

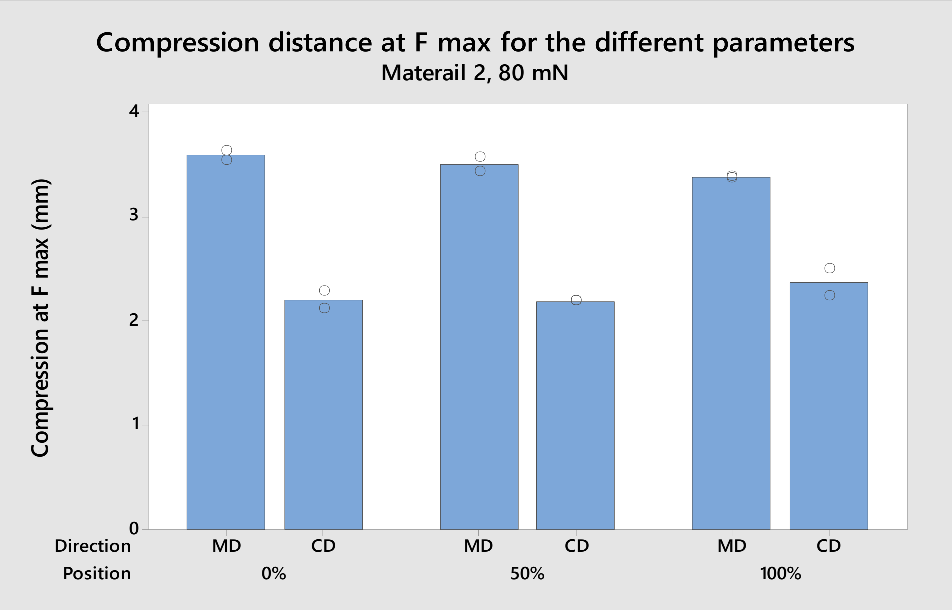

Figure 39 The compressions distance at the maximum registered force for the different positions for material 2. Each direction and position are measured twice.

Figure 40 below shows the pareto chart of the factors affecting the compression distance for material 2. It can be seen that the Direction significantly affects the compression distance.

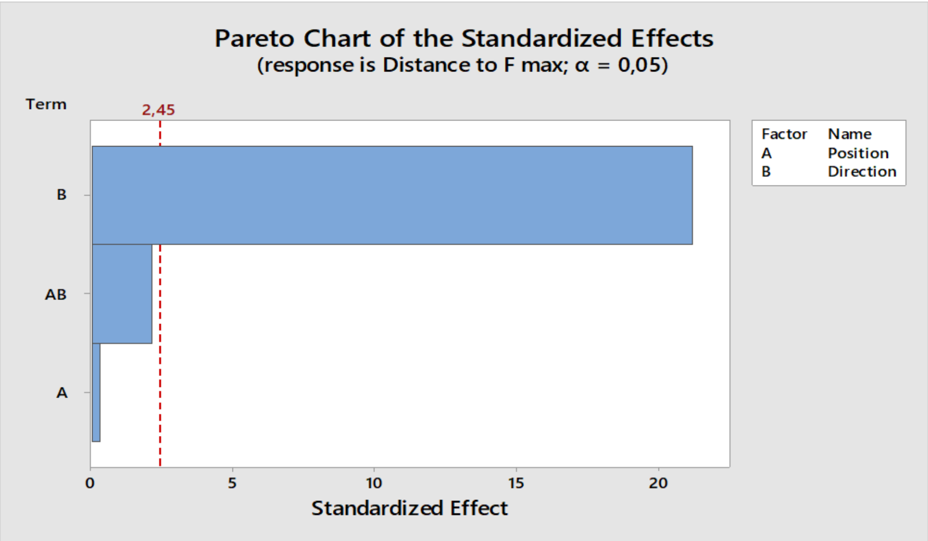

Figure 40 Pareto chart showing the impact of the different factors on the compression distance of material 2. Factor B, the Direction is significant as it crosses the red line.

3.1.10.3.3 Material 3

Both the direction and the position of the crease showed a significant effect on the measurement. The Pareto chart for the test can be seen in Figure 41 below.

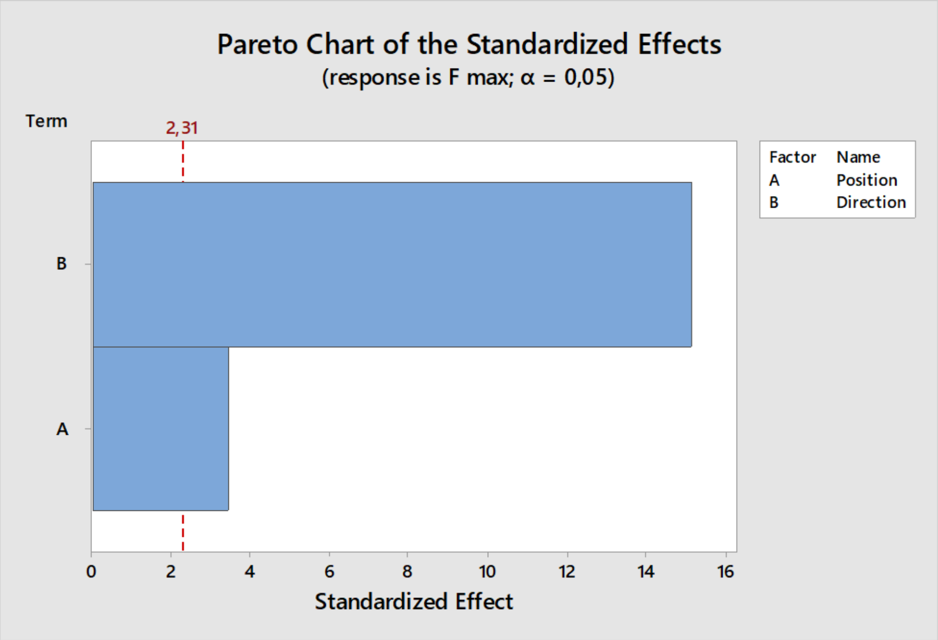

Figure 41 A pareto chart showing the impact of the different factors of material 3. Both factor A, the position, and factor B, the direction, are significant as they cross the red line.

Figure 42 below shows the interaction plot between the measurements. as can be seen, the CD values are higher than the MD values. The difference between the different positions are also larger.

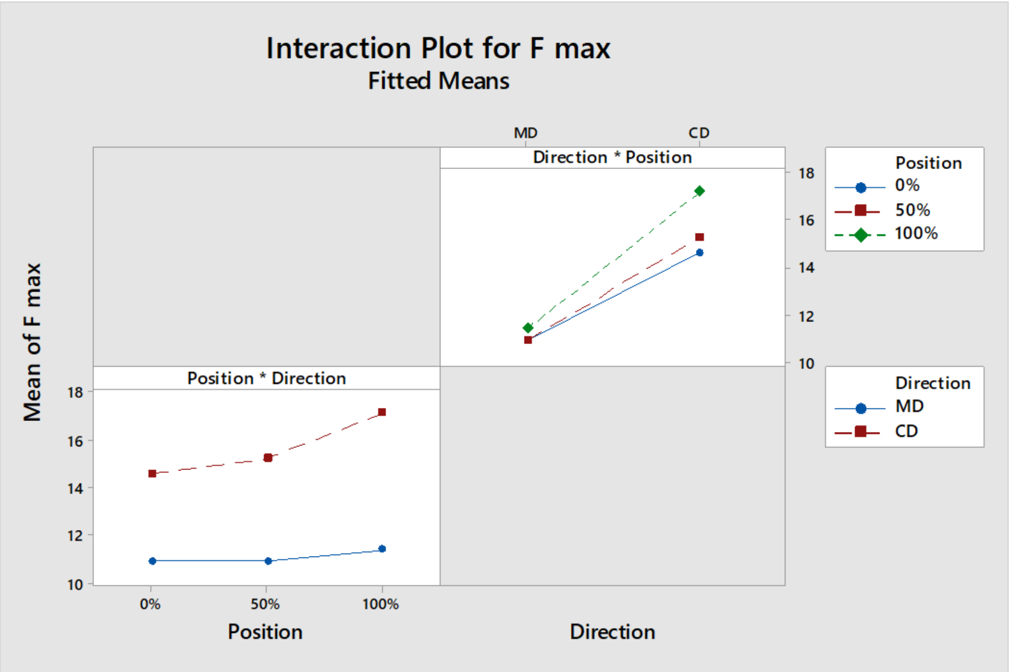

Figure 42 The interaction plot of material 3. The different values for the parameters can be seen.

Figure 43 depicts below the means of the different test parameters.

The model summary of the trial can be seen in Table 24.

Table 24 Model summary of crease position for material 3.

S	R-sq	R-sq(adj)	PRESS	R-sq(pred)
0,0777099	99,95%	99,90%	0,144932	99,79%

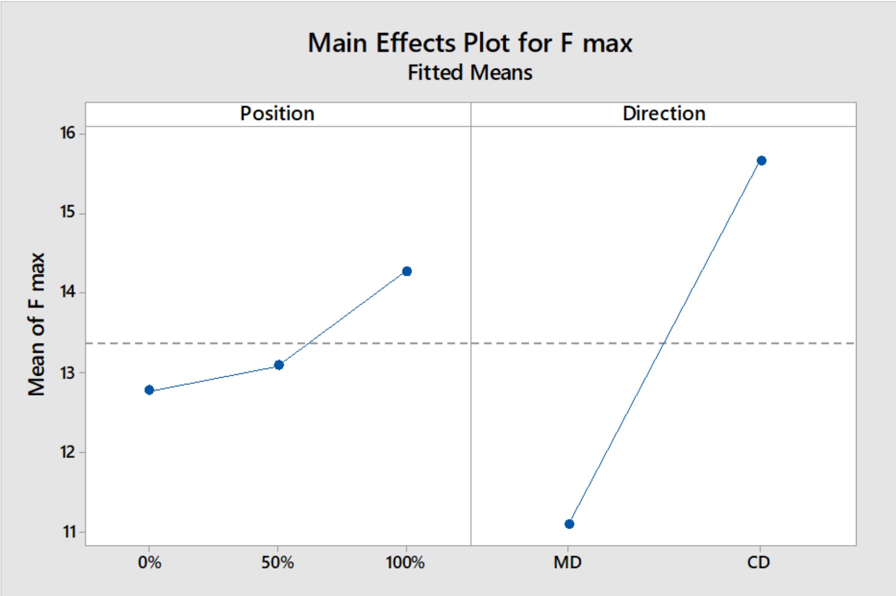

Figure 43 The main effects plot for the test shows the mean result of each parameter for material 3.

The compression distances to the maximum registered force of MD and CD at the three positions can be seen in Figure 44 below.

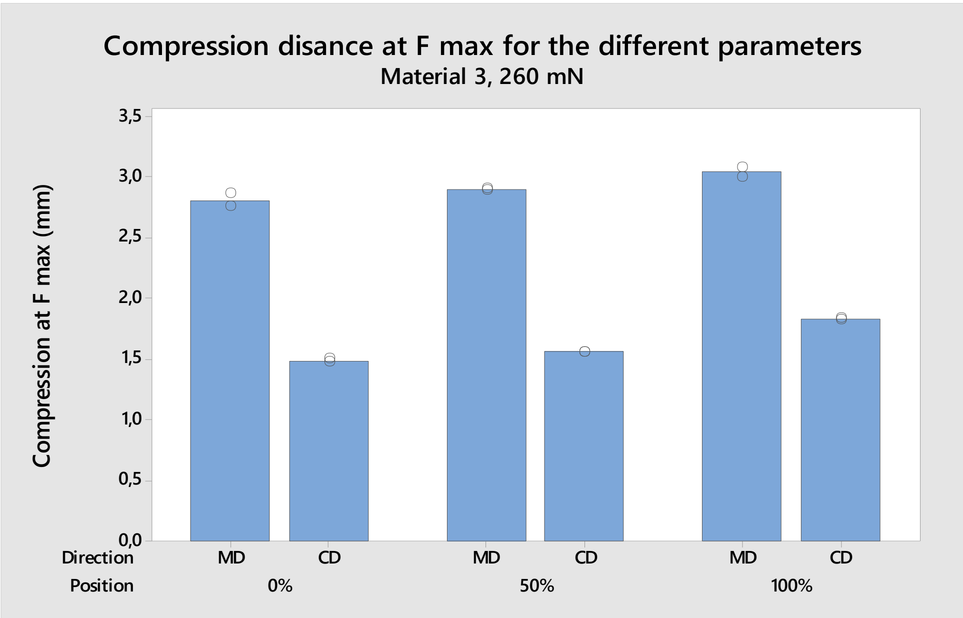

Figure 44 The compressions distance at the maximum registered force for the different positions for material 3.

Figure 45 below shows the pareto chart of the factors affecting the compression distance for material 3. It can be seen that both the direction and the position significantly affects the compression distance.

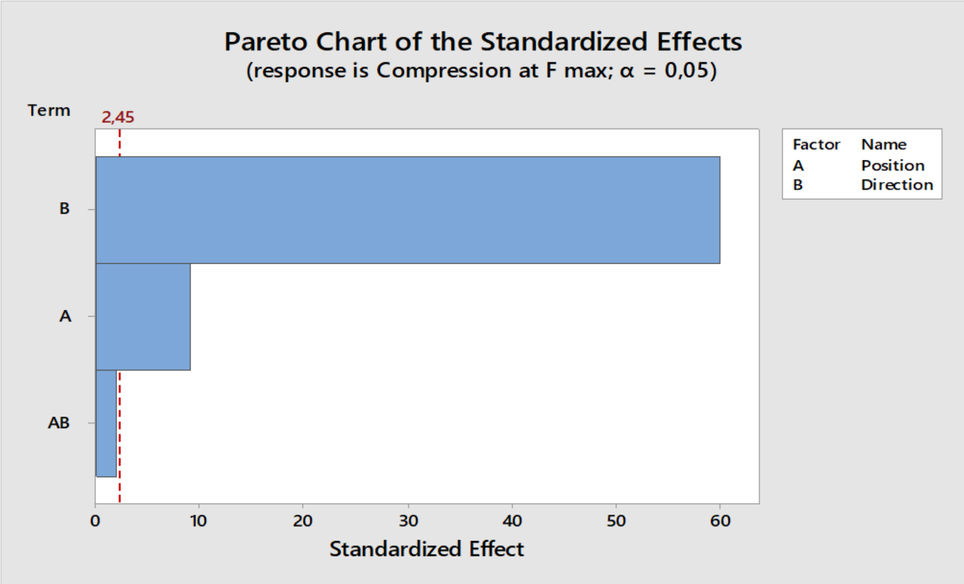

Figure 45 Pareto chart showing the impact of the different factors on the compression distance of material 3. Both factor B, the Direction, and factor A, the Position, is significant as they cross the red line.

3.1.11 Folding direction vs type of packaging material

3.1.11.1 Hypothesis and aim

The aim of the test was to gain information about the impact of the folding direction on the measured max value of a creased sample. As the CD direction generally is proven to be stronger than then MD direction, it would not be surprising if they were statistically different in this test.

3.1.11.2 Settings and parameters

The parameters varied in the test was the folding direction (outside to outside/inside to inside) and the type of the packaging material.

the different types of material in this test was packaging material with normal creasing 80 mN, packaging material with special creasing 80 mN and packaging material with special creasing 260 mN. A compression speed of 100 mm/min was used throughout the test. The samples had the dimensions 38*40 mm with the crease centered. To reduce the effect of the variance of the material, ten samples was used in each measurement and the mean max force was calculated. The samples were conditioned in 22,5 C 50 RH for five days. These tests were performed on the second measuring device.

The design of the experiment can be seen in Table 25 below.

Table 25 The design of the experiment showing the randomized run order and the different settings of the parameters.

StdOrder	RunOrder	PtType	Blocks	Folding Direction	Material
3	1	1	1	Inside Inside	Material 3
7	2	1	1	Inside Inside	Material 1
2	3	1	1	Inside Inside	Material 2
4	4	1	1	Outside Outside	Material 1
12	5	1	1	Outside Outside	Material 3
11	6	1	1	Outside Outside	Material 2
5	7	1	1	Outside Outside	Material 2
10	8	1	1	Outside Outside	Material 1
8	9	1	1	Inside Inside	Material 2
1	10	1	1	Inside Inside	Material 1
6	11	1	1	Outside Outside	Material 3
9	12	1	1	Inside Inside	Material 3

3.1.11.3 Result

Both the folding direction and the material significantly affect the measurement. The Pareto chart for the test can be seen in Figure 46 below.

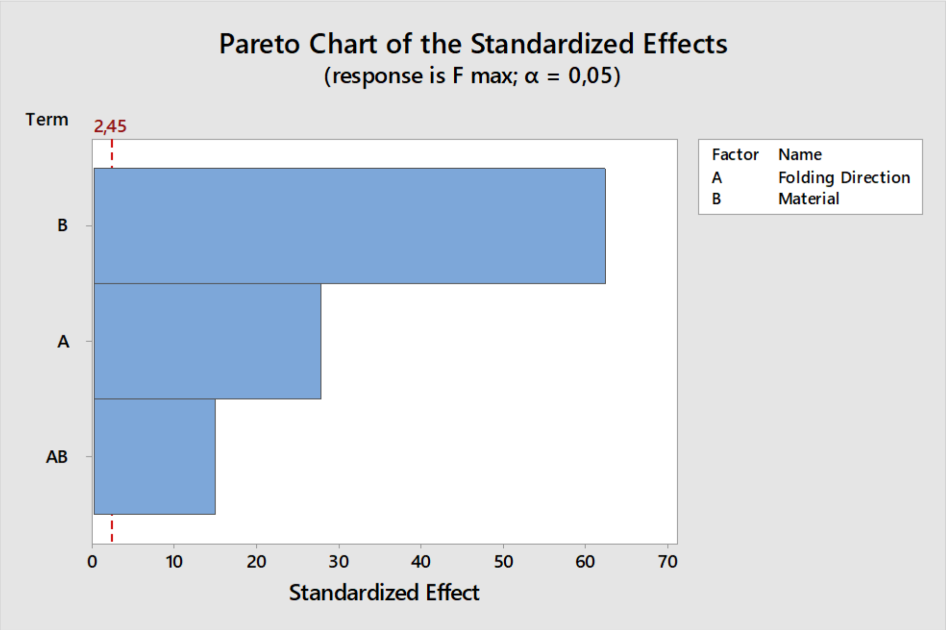

Figure 46 A pareto chart showing the impact of the different factors. Both factor A, the folding direction, and factor B, the material, are significant as they cross the red line.

The model summary of the trial can be seen in Table 26.

Table 26 model summary for folding direction of different materials.

S	R-sq	R-sq(adj)	PRESS	R-sq(pred)
0,0964088	99,91%	99,84%	0,223072	99,65%

Figure 47 depicts below the means of the different test parameters.

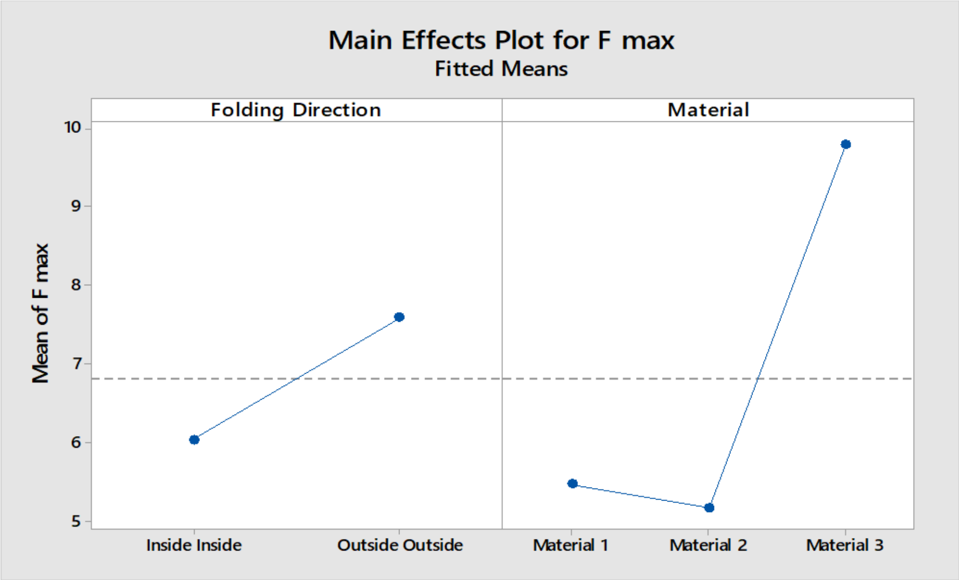

Figure 47 The main effects plot for the test shows the mean result of each parameter for the test.

Figure 48 displays the interaction plot for the test.

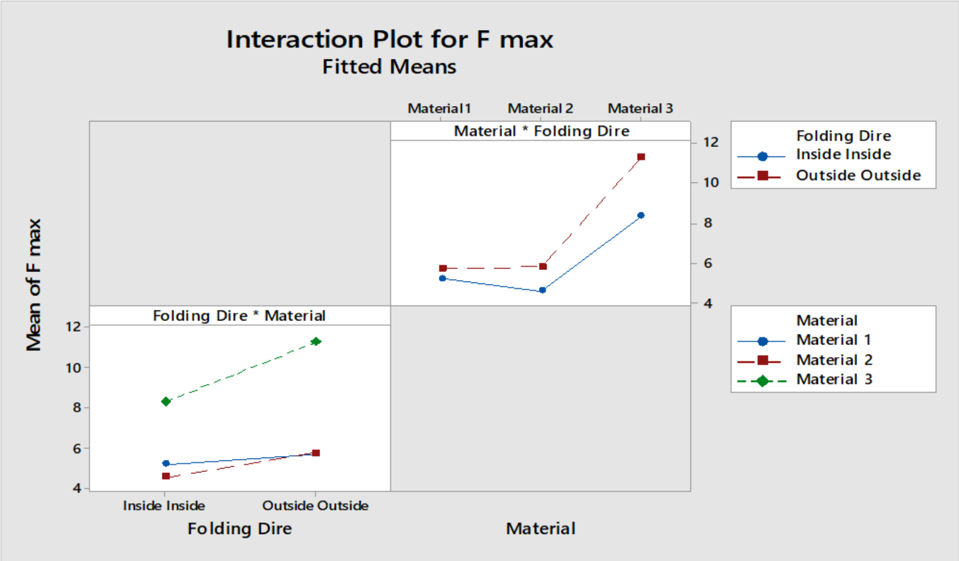

Figure 48 Interaction plot for the test based on F max.

3.2 Suggested method

Preparation of the samples

Condition the material until it has reached equilibrium. Then, using a paper guillotine, cut the material into strips of 38 mm*80 mm diameter with the crease 30 mm from the edge. The strips should be perpendicular to the crease, e.g. a CD crease will have the strip cut in the MD direction.

Measurement of the samples

Attach the fixture to the Instron and choose the recipe for four point bending. Place a sample on the support pins and slowly lower the loading pins until a change in load is detected. Reset the distance and raise it 5 mm. reset the load and the length. Place the crease as centered as possible between the loading pins with the inside facing up. Press the Start button and wait until the loading pins are back in the starting position. Slide the sample to the uncreased side. Make sure the area used for the creased value is not part of the uncreased values area. Press measure. Repeat for all specimens in the batch.

The recommended sample size would have to be established in a later study.

3.3 Result summary

- The factors that significantly affected the measurement were the sample stiffness/thickness, position of crease between loading pins, material direction (MD/CD) and folding direction (inside-inside or outside-outside)
- The factors that did not significantly affect the measurements were compression speed, play in the fixture, angled sample, off centered sample, size of overhang and asymmetric overhang.

4 Part 2 - Verification study

4.1 Method:

A comparison and verification of the new settings were performed. This was done by comparing the new settings of the four-point bending to the ones before the start of this project. The verification was also done by comparing the new method to a modified manually performed I003.5. the modification was done to make the method only measure one crease and not all as it usually does. The number of samples were also modified. Both time and measured values were studied in this comparison. The old four-point bending is more interesting in comparison of time and the modified manual I003.5 method is more interesting for the measured values.

Strips were prepared for all three methods simultaneously. Strips were prepared from two separate materials, one 80 mN stiffness and one 260 mN stiffness. The strips were prepared so that the second MD crease would be measured. Figure 49 shows how the samples were prepared for the different methods. The width of the strips was 38 mm. The strips were conditioned for 7 days in 23 °C 50 %RH. 10 strips per material and method were prepared.

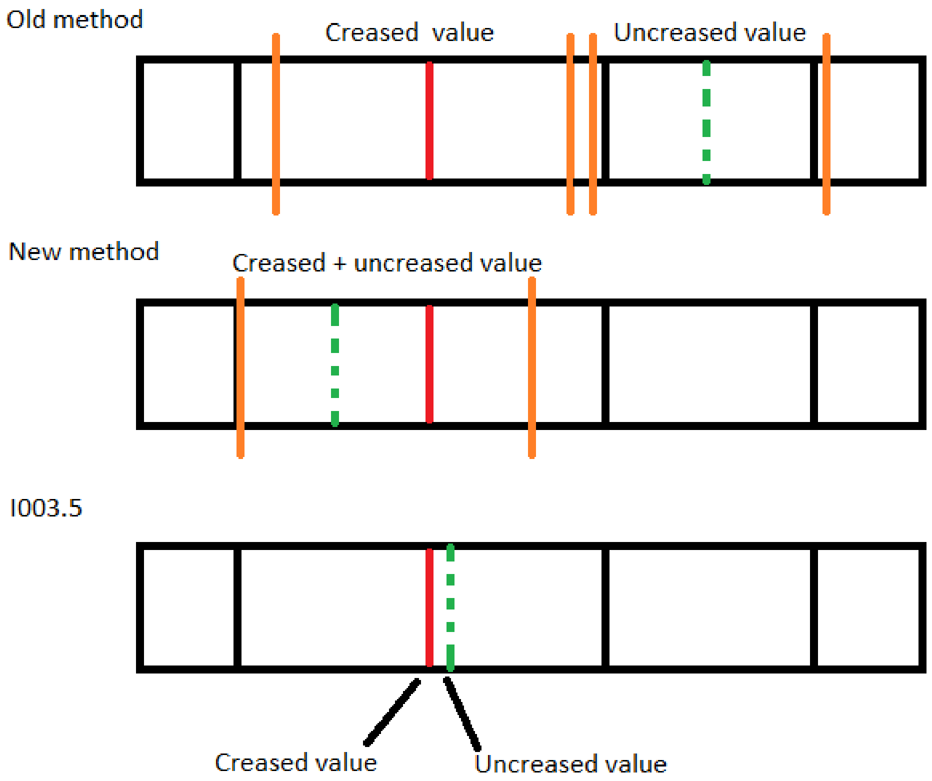

Figure 49 A schematic picture of how the samples were prepared and where they were folded for the three different methods. The red line shows the measured crease, the green line dotted line shows the place of the uncreased value. The orange lines are where the strip was cut.

The time for preparing the samples and the measured values were then compared to each other.

4.2 Result

4.2.1 Relative Crease Strength

The strength of the crease as measured by the different techniques can be seen in Figure 50 below. It can be seen that the two board stiffnesses differ in RCS. The different methods are compared more in detail in the sections below.

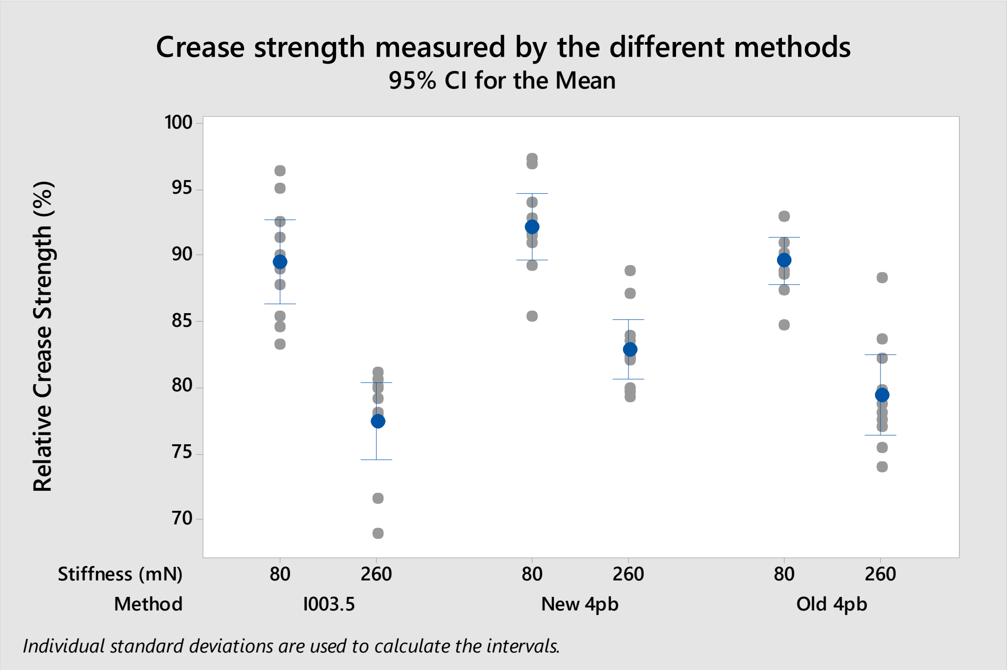

Figure 50 The measured values of both 260 mN material and 80 mN material using the three methods.

4.2.1.1 Material 2

A comparison of the methods for material 2 can be seen in the tukey test in Figure 51. It can be seen that the different methods does not differ statistically. A numerical comparison can be seen in Table 27.

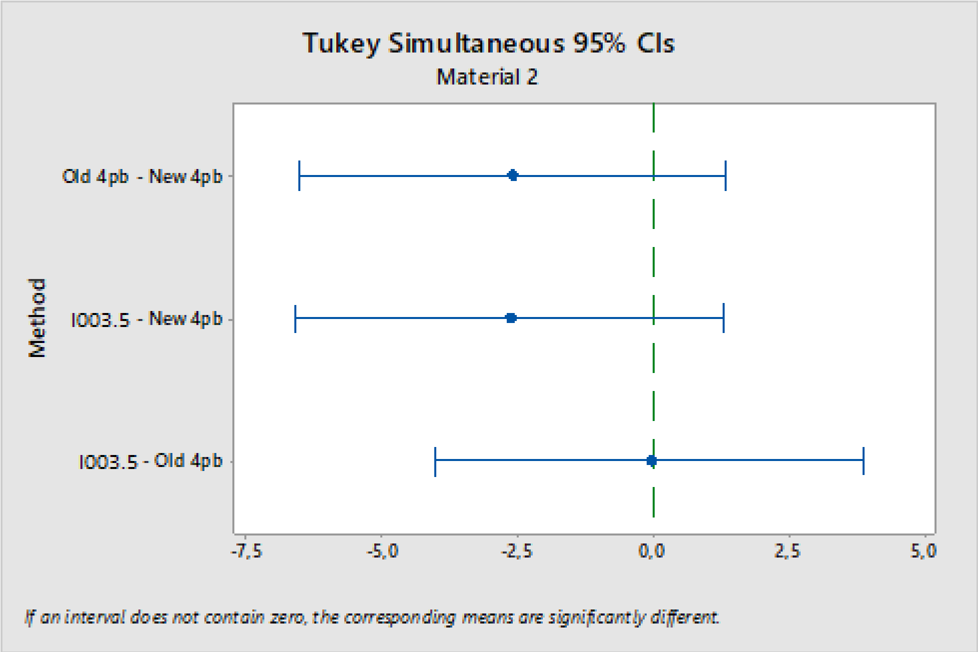

Figure 51 The different methods compared using a tukey test. There is no significant difference between the different methods.

Table 27 A numerical comparison between the different methods for material 2.

Difference of C2 Levels	Difference of Means	SE of Difference	Simultaneous 95% CI	T-Value	Adjusted P-Value
Old 4pb - New 4pb	-2,60	1,59	(-6,54; 1,34)	-1,64	0,247
I003.5 - New 4pb	-2,65	1,59	(-6,59; 1,28)	-1,67	0,234
I003.5 - Old 4pb	-0,05	1,59	(-3,99; 3,89)	-0,03	0,999

Individual confidence level = 98,04%

4.2.1.2 Material 3

A comparison of the methods for material 3 can be seen in the tukey test in Figure 52. It can be seen that the different methods differ. The old four-point bending method is not statistically different to the other two. A numerical comparison can be seen in Table 28.

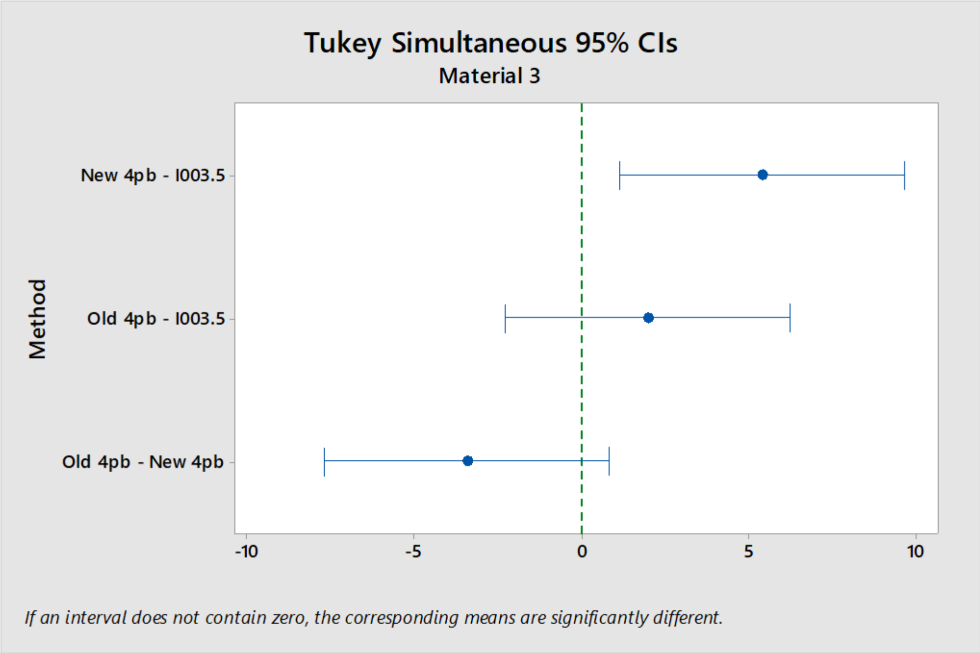

Figure 52 The different methods compared using a tukey test. There is a significant difference for the new four-point bending method compared to the I003.5 method.

Table 28 A numerical comparison between the different methods for material 3.

Difference of Method Levels	Difference of Means	SE of Difference	Simultaneous 95% CI	T-Value	Adjusted P-Value
New 4pb - I003.5	5,40	1,71	(1,15; 9,65)	3,15	0,011
Old 4pb - I003.5	2,00	1,71	(-2,25; 6,25)	1,17	0,483
Old 4pb - New 4pb	-3,40	1,71	(-7,65; 0,85)	-1,99	0,135

Individual confidence level = 98,04%

4.2.2 Time

The time it took to prepare the different samples, the time it took to measure the samples and the total time for preparation and measuring can be seen in the figures below. The starting time of the preparation was set to after the materials were conditioned and cut to strips. It can be seen in Figure 53 that the preparation of the old four-point bending method takes longer time than that of the new one. The time of preparation is however shorter for the I003.5 method than the new four-point bending method.

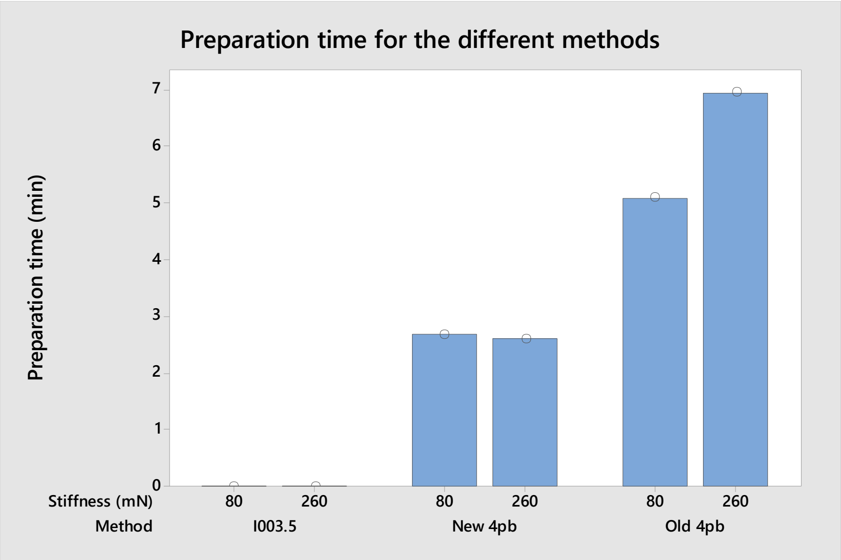

Figure 53 The time it took to prepare the samples after conditioning the strips.The time is measured from when the material was cut into strips.

It can be seen in Figure 54 that the new four-point bending method is the fastest method to perform the measurements with compared to the old one and the modified I003.5 method.

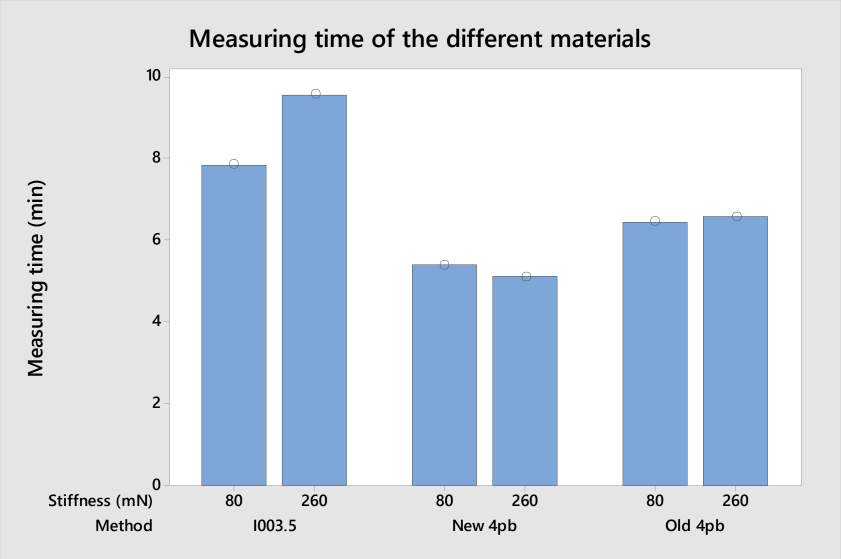

Figure 54 The time it took to perform the measurements using the different methods.

Overall, it can be seen in Figure 55 that the new four point bending is in the same time range as the I003.5 method in the overall time after the strips have been prepared with the old four-point bending method being longer.

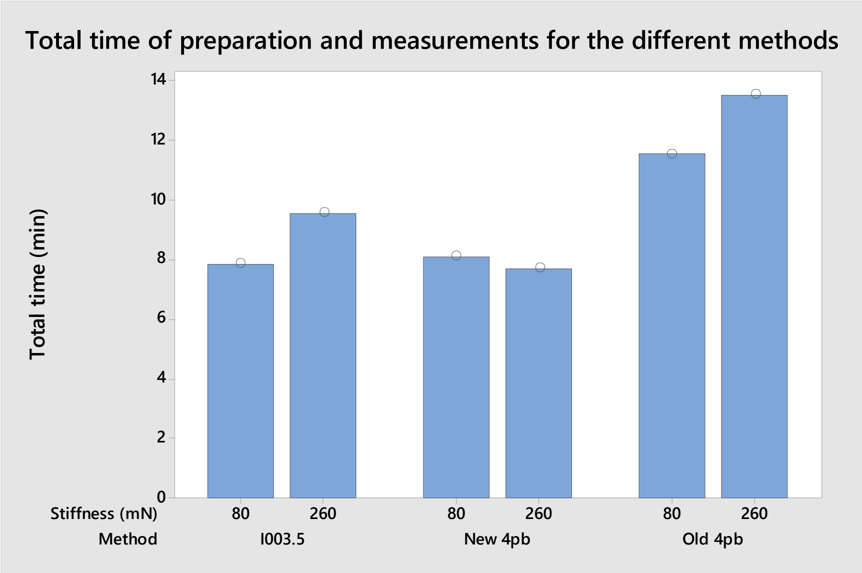

Figure 55 the total time it took to prepare the samples and perform the measurements using the different methods.

5 Discussion

The results from the parameter study gave a lot of information about how the proposed method for four-point bending should be carried out by the operator. Below, the different results are discussed.

5.1 Compression speed

As seen in the results from the study of the compression speed vs thickness of paperboard, the speed does not significantly affect the outcome of the measurement even though the material is viscoelastic. This would suggest that at these compression speeds and stiffnesses of the paperboards, the materials are still similar enough to not indicate a difference in resistance to bend due to speed. Because of this, materials that are between 80 and 260 mN should be carried out at the maximum speed investigated in the study (100 mm/min). Should a material thicker than 260 mN or thinner than 80 mN be measured, extra tests verifying that the speed of 100 mm/min can be used without affecting the measurement. The reason to why a high compression speed is wanted is that it reduces the time of the test. The maximum speed investigated in this study will thereby be used in the suggested method. At 100 mm/min, each measurement is performed in less than 10 seconds.

5.2 Angled sample

The study of how the sample is placed in the fixture regarding a straight or angled sample, showed that there was not statistical difference between the two positions. This test was performed using a metal sample as to eliminate any variance in the material. However, as metal is not anisotropic, material composed of paperboard could behave differently. The geometry of the sample also means that when the sample is placed at an angle in the fixture, the width of the sample will act wider than that in the case of a straight sample since the loading pins always push down with the same geometry (Figure 56). The wider the sample is, the more this will impact the measurement as the length of the bend increases faster. As the metal sample had a width of 25 mm, but the preferred sample size is 38 mm, this could show to be crucial. This phenomenon can be seen as a trend in the measurement performed, where the angled samples has slightly higher values than the aligned one. Perhaps in the case of a larger sample size this would show a significant difference. However, as mentioned above, this measurement is performed using metal samples and not packaging material. The packaging material will be strongest when the most fibers are perpendicular to the bending direction (Li et al., 2016). This would suggest that the more angled the material is, the weaker the material would be due to the misalignment of fibers. However, when performing the standard operating procedure, it is advised to try to place the sample as straight as possible. Moreover, the wider the sample is, the easier it is to place the sample more straight in the fixture. In hindsight, this test should have been performed using both uncreased packaging material samples and creased packaging material samples. The creased samples would most likely add some shear moment which could have affected the measurement.

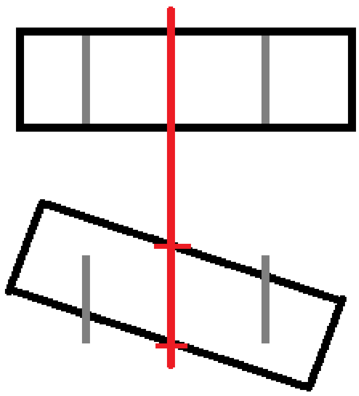

Figure 56 The angled sample will have a longer bend than the straight sample.

5.3 Play in loading pins

The study of the play in the loading pins showed that while there is some play in the loading pins, the play can be neglected. It was also observed that the extreme position corrected itself to a more centered position as the measurement progressed. The same reasoning as above can be used to argue that the misalignment of the loading pins will see the sample as wider than it is. The play is however low enough that this does not affect the measurement, as shown.

5.4 Off-centered sample

In the study of how the positioning in the depth affected the measurement, it was found that it did not impact the measurement in any significant way. This test was performed with a 25 mm thick metal sample and it is possible that the width of the sample does matter, especially if the sample is narrow enough to not contain the center of the loading pins as this could introduce a moment in the loading pin fixture. However, the preferred width of the samples is 38 mm and at this size the sample will cover almost the entire area, meaning that no matter how the sample is placed, the difference will be minimal. It would only be in certain cases where there is an interfering crease that a smaller strip should be prepared. The method I003.5 suggests that the narrowest strip is 19 mm, which would just barely not cover the center of the fixture if aligned with the edge of the fixture. It is however advised to center the sample as much as possible during the standard operating procedure as this would eliminate this potential problem.

5.5 Overhang

The overhang studies showed that the impact of the overhang in both the case of size and mis centered could be neglected. This indicates that the moving parts of the sample does not impact the measurements in a major way. Due to this, both measurement of the crease and the uncreased material can be performed using the same sample. This is convenient as it saves time during the preparation of cutting the samples. However, the samples with the length of 100 mm were slightly too long as they interfered with the loading cell due to the large deflections as can be seen in

Figure 57. This suggests that the sample length should be around 80 mm length to avoid this. To be able to measure the creased and the uncreased material on the same piece, the crease should not be centered on the sample due to the fact that the first bend cannot be within the support pins of the second one, and there is some sliding taking place during the test. It is also not very convenient for the operator to manage a test where the margin to the edge of the sample is very low, as it can be tricky to predict how much the material will slide due to varying lengths of compression. It was however seen during the trials of the new four-point bending that a sample length of 80 mm might not be the best as it sometimes interfered with the load cell when measuring the uncreased value as shown in Figure 58. The interference did not affect the peak value as this had already been reached when the interfering

took place. This problem with the sample interfering with the load cell can be fixed by either having the crease more towards the edge of the sample, meaning that the uncreased value is taken at a more centered position of the sample. Another way to do it is to shorten the length of the sample. The suggested sample dimensions can be seen in Figure 59.

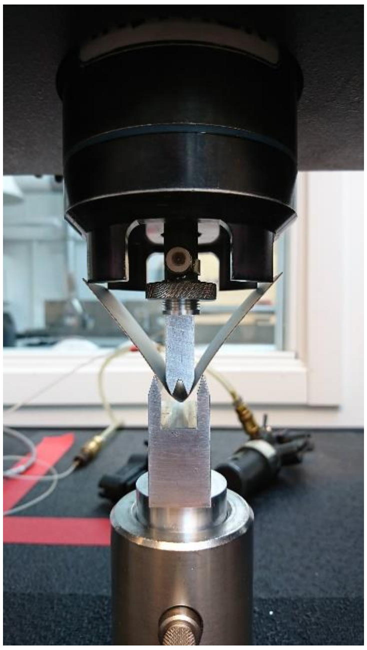

Figure 57 Measurement of a 100 mm sample, the flaps start to interact with the load cell at large deflections.

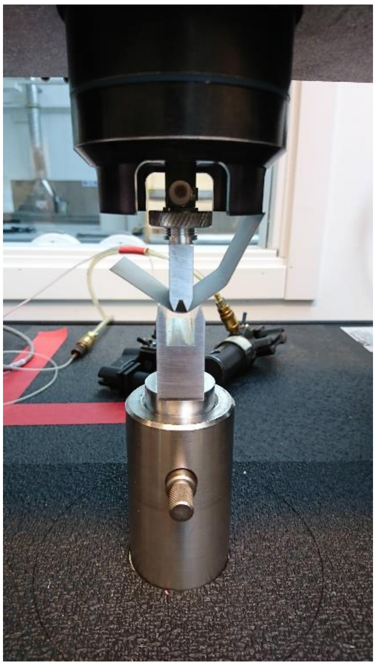

Figure 58 The samples interfering with the load cell during the measurement of the uncreased value.

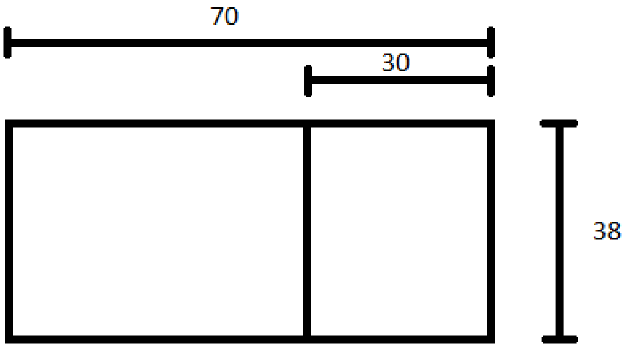

Figure 59 The suggested sample dimensions.

5.6 Position between loading pins

The studies regarding the positioning of the crease between the loading pins shows that there is no statistical significance in the difference between the three positions for the 80 mN materials. However, in the 260 mN material there were a statistical difference between the case where the crease was directly beneath the loading pin and the two other positions. The positions where the crease was between the loading pins showed no statistical difference. This is a wanted and expected result for the 260 mN material as the method should find the weakest spot between the loading pins and bend the sample there. When the crease was positioned beneath the loading pins, the sample was still folded in the crease, but the bending behaved differently as the crease sometimes lost contact with the loading pin. This caused a part of the measurement to be three-point bending instead of four-point bending. This gives the bending a different momentum as the loading pin was not placed at the weakest point which should be the case in three-point bending (Gullichsen et al., 1999). The measured maximum peak was however always occurring during the four-point bending phase. However, during this bend, the crease was forced into a more centered position between the loading pins. This would suggest that there is a large amount of sliding involved in the case of measuring this position compared to the other two positions. The influence of friction could not be performed in this study as the time and material was a limiting factor, but this is something that should be further investigated in the future. Something to note was that the influence of the position was bigger in the CD direction than in the MD direction of the samples. This suggests that the position of the crease does have some influence on the measured value. The reason to this finding could possibly be due to the fiber orientation of the material. Additional measurements should be performed to verify that this is true. The 80 mN materials should follow the same logic as the 260 mN material but there is no statistical difference between the three positions. There is however a trend that could indicate that the position where the crease is directly beneath the loading pin has a higher value than the other two. Perhaps if more samples were measured these would show a statistical difference too.

5.7 Material direction

The direction of the crease in the material (MD/CD) had a significant impact on all materials investigated. This is an expected result as the main reason for stiffness and rigidity is the fibers, which due to how the paperboard is produced, are stronger in the MD direction (Li et al., 2016). This causes the CD creases to have a higher value than the MD creases as the CD creases are measured in the MD direction.

5.8 Folding direction

The study of folding the material inside to inside or outside to outside showed that the difference between the two directions were significant. The reason to this is that the material is not symmetrical in the ZD direction. This means that the aluminum and the polymers will stretch different amounts depending on how the package is placed in the fixture. However, the operator should be able to identify which side of the material that is the inside and which one that is the outside and place the sample accordingly. It is important to note that there are parts of the package in which both inside to inside fold and outside to outside folds are present, meaning that both are of relevance. The measurement for the 260 mN material inside to inside showed a different behavior than the rest of the measurements. There were two peaks when measuring this case. This is probably due to the thickness of the material being forced against itself in the crease after a certain time, adding extra resistance to bend.

5.9 General

Overall the R^2-Pred was high, especially when refined by removing the nonsignificant factors. A lot of the time this meant that the stiffness or thickness was the only significant factor taken into account, which explains why they are all in roughly the same range.

The different parameters investigated in this study did not affect the compression distance to the maximum load in a major way except if the material was measured in MD or CD. The fact that the MD and CD is different could be explained by the direction of the fibers. The MD crease, which is folded parallel to the fibers needs to be deformed than the CD crease, before the collapse of the material can be noted. The compression distance did not vary for the different stiffnesses within the same kind of material.

Studies of the friction could not be made in the test due to limitations of time and resources but as there is a decent amount of sliding present during the measurements it would not be surprising if it showed a significant impact.

5.10 Relative crease strength comparison

As seen in t-tests comparing the measured crease strength in the verification study, there is a significant difference between the new four-point bending method and the I003.5 method for the 260 mN material. This is interesting as both methods compare the bending force required to bend the sample in the crease and in an uncreased area and compare the two values. The fact that they differ in this study could be due to the different load case that is present in the two methods. I003.5 clamps the samples a certain distance away from the crease, controlled by the operator, and forces the sample to bend there. The four point-bending on the other hand, lets the sample rest on the support pins and is then bent in the weakest spot on the sample. This should however be further investigated by repeating the measurement with different operators, as the manual I003.5 value is previously shown to be operator dependent. In all other cases there is no statistical difference between the methods, but there is a trend that the new four-point bending method measures a slightly higher value. Never the less, they are in the same range and this could be a onetime observation. Again, additional studies should be made to control this.

This test was performed using 10 consecutive packages from the same reel. This means that the different packages were not creased by the same creasing plate. The reason this was done was that material and time was a limit. If the same creasing plate was compared for all the samples, the variance between the samples could potentially be smaller and there might not be a significant difference between the methods. It is also important to note that the amount of creasing plates on the creasing tool was of a number which did not have a multiplier of 10. This means that the different batches have different amounts of packages from different creasing plates, e.g. not all methods were tested with three packages from creasing tool one. this could impact the mean values of the measurement. This also means that the specimes are not independent of each other, which could impact the analyses of the results.

It could be that since the load case is different, the two method can not be directly compared. However, both methods are constructed to measure the same thing, and a comparison between them could be considered a guideline when deciding if the new method is legit to use.

5.11 Time comparison

The measured time it took to prepare and perform the measurements for the different methods shows that the new four-point bending is the fastest method of the three. It is however interesting that the I003.5 varies almost 2 minutes between the two thicknesses. This could be due to the 260 mN being done before the 80 mN and the muscle memory of how to measure was a factor. It could however also be that the 260 material is thick enough that it becomes harder to move when clamped, meaning that it is harder to position correctly when measuring the creased value and takes a longer time to move into position when the uncreased value should be measured. However, as the manual I003.5 method was modified, the time aspect is not corresponding to the methods normal usage.

In the plot it can also be seen that the new four-point bending is faster than the old one in both the preparation of the samples and during the measurement itself. The reason to why it is faster during the preparation is that the old method required two pieces á 80 mm and the new one only requires one. Using the old method, the 80 mN material was faster to prepare than the 260 mN one. This was due to the size of the strip, which caused one cut from the strip to be left out as the second test piece was taken directly after the first one. One thing to note is that the old method did not have a good way of measuring the first and the fourth crease of materials with a short web width as the crease can be closer to the edge than 40 mm.

The new four-point bending method is also faster than the old one during the measurements. This is the case due to the old one again having two pieces and the new one only having one. Moving the one sample of the new one between the creased and the uncreased position was faster than removing the bent sample and replacing it with a new sample which again must be centered.

It is important to note that the start point for the time was after the materials were conditioned and cut to strips. This results in that the preparation time for the I003.5 method is zero, as no additional steps between cutting of the material and the measurement is occurring, whereas four-point bending needs to reduce the size of the strips to 80 mm samples.

To establish that the time for performing the different methods are true, additional trials should be performed by different operators.

6 Conclusion

Below are the summarized conclusions found in this project.

- The factors that significantly affected the measurement were the sample stiffness/thickness, crease position between loading pins, material direction (MD/CD) and folding direction (inside-inside or outside-outside)
- The factors that did not significantly affect the measurements were compression speed, play in the fixture, angled sample, off centered sample, size of overhang and asymmetric overhang.
- The proposed method is faster than the old four-point bending method and about as fast the current I003.5 method.
- The relative crease strength obtained using the new method differs from the one obtained using the manual I003.5 method but not the old four-point bending method. The old four-point bending method did not differ from the I003.5 method.
- The compression distance recorded at the maximum force was in the range of 1,5-3 mm using this fixture.

7 Future work

The project that I was a part of was bigger than I first expected, and I have only scratched the surface. Although this thesis has resulted in a basic understanding of how the different parameters impact the measurements, additional work with larger sample sizes and other operators should be performed to investigate the trends that I suspect might be true but cannot prove due to my sample size. Additional parameters, such as the friction, that I did not have the time to test in this thesis could also be investigated to further refine the method. As shown in the study, the different direction (MD/CD) had an impact of the measurements and it would be good to perform the different tests on both of these and not just MD as I did. The recommended sample size should also be decided upon before the method can be used in the industry. Additional operators should perform the verification of the method to gain some more data to compare and this should be performed on several different materials as the one I measured had a rather high relative crease strength. A final validation of the method is also required before it can be used in the industry.

I think it would be good to sometime in the future also develop an own measuring device that automatically places the sample correctly in the fixture.

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9 Appendix 1 – Load cell information

Load cell	Model/Serial number
1	Force_TC 100N – 2525-807/UK490
2	Force_TC 100N – 2518-807/UK1424

10 Appendix 2 – Statistical data

10.1 Compression speed vs thickness of metal

Data evaluation of F max accounting for all parameters, significant or not.

Analysis of Variance

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value
Model	3	109,217	97,36%	109,217	36,406	86,05
Linear	2	109,216	97,36%	109,216	54,608	129,08
Compression speed	1	0,001	0,00%	0,001	0,001	0,00
Thickness	1	109,215	97,36%	109,215	109,215	258,16
2-Way Interactions	1	0,001	0,00%	0,001	0,001	0,00
Compression speed*Thickness	1	0,001	0,00%	0,001	0,001	0,00
Error	7	2,961	2,64%	2,961	0,423	
Curvature	1	2,952	2,63%	2,952	2,952	1900,56
Pure Error	6	0,009	0,01%	0,009	0,002	
Total	10	112,178	100,00%			

Source	P-Value
Model	0,000
Linear	0,000
Compression speed	0,966
Thickness	0,000
2-Way Interactions	0,962
Compression speed*Thickness	0,962
Error	
Curvature	0,000
Pure Error	
Total	

Model Summary

S	R-sq	R-sq(adj)	PRESS	R-sq(pred)
0,650427	97,36%	96,23%	5,45250	95,14%

Coded Coefficients

Term	Effect	Coef	SE Coef	95% CI	T-Value	P-Value	VIF
Constant		4,583	0,196	(4,119; 5,047)	23,37	0,000	
Compression speed	-0,020	-0,010	0,230	(-0,554; 0,534)	-0,04	0,966	1,00
Thickness	7,390	3,695	0,230	(3,151; 4,239)	16,07	0,000	1,00
Compression speed*Thickness	-0,023	-0,011	0,230	(-0,555; 0,532)	-0,05	0,962	1,00

Regression Equation in Uncoded Units

F max = -6,54 + 0,0006 Compression speed + 185,6 Thickness
- 0,014 Compression speed*Thickness

Data evaluation of F max accounting only for the significant terms

Analysis of Variance

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Model	1	109,215	97,36%	109,215	109,215	331,70	0,000
Linear	1	109,215	97,36%	109,215	109,215	331,70	0,000
Thickness	1	109,215	97,36%	109,215	109,215	331,70	0,000
Error	9	2,963	2,64%	2,963	0,329		
Curvature	1	2,952	2,63%	2,952	2,952	2105,92	0,000
Lack-of-Fit	2	0,002	0,00%	0,002	0,001	0,61	0,574
Pure Error	6	0,009	0,01%	0,009	0,002		
Total	10	112,178	100,00%				

Model Summary

S	R-sq	R-sq(adj)	PRESS	R-sq(pred)
0,573806	97,36%	97,06%	3,92553	96,50%

Coded Coefficients

Term	Effect	Coef	SE Coef	95% CI	T-Value	P-Value	VIF
Constant		4,583	0,173	(4,192; 4,974)	26,49	0,000	
Thickness	7,390	3,695	0,203	(3,236; 4,154)	18,21	0,000	1,00

Regression Equation in Uncoded Units

F max = -6,501 + 184,7 Thickness

10.2 Compression speed vs stiffness of paperboard

Data evaluation of F max accounting for all parameters, significant or not.

Analysis of Variance

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value
Model	3	42,2453	97,35%	42,2453	14,0818	97,93
Linear	2	42,2306	97,32%	42,2400	21,1200	146,87
Compression speed	1	0,2867	0,66%	0,2961	0,2961	2,06
Board stiffness	1	41,9439	96,65%	41,9439	41,9439	291,69
2-Way Interactions	1	0,0148	0,03%	0,0148	0,0148	0,10
Compression speed*Board stiffness	1	0,0148	0,03%	0,0148	0,0148	0,10
Error	8	1,1504	2,65%	1,1504	0,1438	
Curvature	1	0,0086	0,02%	0,0086	0,0086	0,05
Lack-of-Fit	4	1,1161	2,57%	1,1161	0,2790	32,60
Pure Error	3	0,0257	0,06%	0,0257	0,0086	
Total	11	43,3957	100,00%			

Source	P-Value
Model	0,000
Linear	0,000
Compression speed	0,189
Board stiffness	0,000
2-Way Interactions	0,757
Compression speed*Board stiffness	0,757
Error	
Curvature	0,825
Lack-of-Fit	0,008
Pure Error	
Total	

Model Summary

S	R-sq	R-sq(adj)	PRESS	R-sq(pred)
0,379207	97,35%	96,35%	2,16276	95,02%

Coded Coefficients

Term	Effect	Coef	SE Coef	95% CI	T-Value	P-Value
Constant		6,424	0,110	(6,171; 6,678)	58,45	0,000
Compression speed	0,446	0,223	0,155	(-0,135; 0,581)	1,43	0,189
Board stiffness	4,542	2,271	0,133	(1,964; 2,578)	17,08	0,000
Compression speed*Board stiffness	0,120	0,060	0,188	(-0,373; 0,494)	0,32	0,757

Term	VIF
Constant	
Compression speed	1,01
Board stiffness	1,00
Compression speed*Board stiffness	1,01

Regression Equation in Uncoded Units

Fmax = 1,970 + 0,00273 Compression speed + 0,02423 Board stiffness
+ 0,000017 Compression speed*Board stiffness

Data evaluation of F max accounting only for the significant terms.

Analysis of Variance

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Model	1	41,9439	96,65%	41,9439	41,9439	288,91	0,000
Linear	1	41,9439	96,65%	41,9439	41,9439	288,91	0,000
Board stiffness	1	41,9439	96,65%	41,9439	41,9439	288,91	0,000
Error	10	1,4518	3,35%	1,4518	0,1452		
Curvature	1	0,0086	0,02%	0,0086	0,0086	0,05	0,822
Lack-of-Fit	6	1,4176	3,27%	1,4176	0,2363	27,61	0,010
Pure Error	3	0,0257	0,06%	0,0257	0,0086		
Total	11	43,3957	100,00%				

Model Summary

S	R-sq	R-sq(adj)	PRESS	R-sq(pred)
0,381026	96,65%	96,32%	1,97732	95,44%

Coded Coefficients

Term	Effect	Coef	SE Coef	95% CI	T-Value	P-Value	VIF
Constant		6,424	0,110	(6,178; 6,670)	58,17	0,000	
Board stiffness	4,542	2,271	0,134	(1,973; 2,569)	17,00	0,000	1,00

Regression Equation in Uncoded Units

Fmax = 2,134 + 0,02523 Board stiffness

10.3 Play in loading pin vs thickness of metal

Data evaluation of F max accounting for all parameters, significant or not.

Analysis of Variance

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Model	3	54,1147	94,48%	54,1147	18,0382	22,81	0,006
Linear	2	54,1144	94,48%	54,1144	27,0572	34,21	0,003
Thickness	1	54,1118	94,47%	54,1118	54,1118	68,41	0,001
Position	1	0,0025	0,00%	0,0025	0,0025	0,00	0,958
2-Way Interactions	1	0,0004	0,00%	0,0004	0,0004	0,00	0,984
Thickness*Position	1	0,0004	0,00%	0,0004	0,0004	0,00	0,984
Error	4	3,1638	5,52%	3,1638	0,7909		
Curvature	1	3,1629	5,52%	3,1629	3,1629	10645,56	0,000
Lack-of-Fit	1	0,0001	0,00%	0,0001	0,0001	0,13	0,753
Pure Error	2	0,0008	0,00%	0,0008	0,0004		
Total	7	57,2785	100,00%				

Model Summary

S	R-sq	R-sq(adj)	PRESS	R-sq(pred)
0,889347	94,48%	90,33%	28,1163	50,91%

Coded Coefficients

Term	Effect	Coef	SE Coef	95% CI	T-Value	P-Value	VIF
Constant		4,233	0,314	(3,360; 5,106)	13,46	0,000	
Thickness	7,356	3,678	0,445	(2,443; 4,913)	8,27	0,001	1,00
Position	-0,035	-0,018	0,314	(-0,891; 0,855)	-0,06	0,958	1,00
Thickness*Position	-0,019	-0,009	0,445	(-1,244; 1,225)	-0,02	0,984	1,00

Regression Equation in Uncoded Units

Fmax = -6,80 + 183,9 Thickness + 0,01 Position - 0,5 Thickness*Position

Data evaluation of F max accounting only for the significant terms.

Analysis of Variance

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Model	1	54,1118	94,47%	54,1118	54,1118	102,53	0,000
Linear	1	54,1118	94,47%	54,1118	54,1118	102,53	0,000
Thickness	1	54,1118	94,47%	54,1118	54,1118	102,53	0,000
Error	6	3,1666	5,53%	3,1666	0,5278		
Curvature	1	3,1629	5,52%	3,1629	3,1629	4195,07	0,000
Lack-of-Fit	3	0,0029	0,01%	0,0029	0,0010	2,34	0,314
Pure Error	2	0,0008	0,00%	0,0008	0,0004		
Total	7	57,2785	100,00%				

Model Summary

S	R-sq	R-sq(adj)	PRESS	R-sq(pred)
0,726479	94,47%	93,55%	6,12146	89,31%

Coded Coefficients

Term	Effect	Coef	SE Coef	95% CI	T-Value	P-Value	VIF
Constant		4,233	0,257	(3,605; 4,862)	16,48	0,000	
Thickness	7,356	3,678	0,363	(2,789; 4,567)	10,13	0,000	1,00

Regression Equation in Uncoded Units

Fmax = -6,80 + 183,9 Thickness

10.4 Angled and straight samples vs thickness of metal

Data evaluation of F max accounting for all parameters, significant or not.

Analysis of Variance

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Model	3	61,3778	95,11%	61,3778	20,4593	25,94	0,004
Linear	2	61,0699	94,63%	61,0699	30,5349	38,72	0,002
Thickness	1	60,3539	93,52%	60,3539	60,3539	76,53	0,001
Position	1	0,7160	1,11%	0,7160	0,7160	0,91	0,395
2-Way Interactions	1	0,3079	0,48%	0,3079	0,3079	0,39	0,566
Thickness*Position	1	0,3079	0,48%	0,3079	0,3079	0,39	0,566
Error	4	3,1546	4,89%	3,1546	0,7887		
Curvature	1	3,1160	4,83%	3,1160	3,1160	241,91	0,001
Lack-of-Fit	1	0,0385	0,06%	0,0385	0,0385	498,43	0,002
Pure Error	2	0,0002	0,00%	0,0002	0,0001		
Total	7	64,5324	100,00%				

Model Summary

S	R-sq	R-sq(adj)	PRESS	R-sq(pred)
0,888065	95,11%	91,45%	28,0401	56,55%

Coded Coefficients

Term	Effect	Coef	SE Coef	95% CI	T-Value	P-Value	VIF
Constant		4,483	0,314	(3,611; 5,355)	14,28	0,000	
Thickness	7,769	3,884	0,444	(2,652; 5,117)	8,75	0,001	1,00
Position	-0,598	-0,299	0,314	(-1,171; 0,573)	-0,95	0,395	1,00
Thickness*Position	-0,555	-0,277	0,444	(-1,510; 0,955)	-0,62	0,566	1,00

Regression Equation in Uncoded Units

F max = -7,17 + 194,2 Thickness + 0,53 Position - 13,9 Thickness*Position

Data evaluation of F max accounting only for the significant terms.

Analysis of Variance

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Model	1	60,3539	93,52%	60,3539	60,3539	86,66	0,000
Linear	1	60,3539	93,52%	60,3539	60,3539	86,66	0,000
Thickness	1	60,3539	93,52%	60,3539	60,3539	86,66	0,000
Error	6	4,1785	6,48%	4,1785	0,6964		
Curvature	1	3,1160	4,83%	3,1160	3,1160	14,66	0,012
Lack-of-Fit	3	1,0624	1,65%	1,0624	0,3541	4586,11	0,000
Pure Error	2	0,0002	0,00%	0,0002	0,0001		
Total	7	64,5324	100,00%				

Model Summary

S	R-sq	R-sq(adj)	PRESS	R-sq(pred)
0,834520	93,52%	92,45%	8,47845	86,86%

Coded Coefficients

Term	Effect	Coef	SE Coef	95% CI	T-Value	P-Value	VIF
Constant		4,483	0,295	(3,761; 5,205)	15,19	0,000	
Thickness	7,769	3,884	0,417	(2,863; 4,905)	9,31	0,000	1,00

Regression Equation in Uncoded Units

F max = -7,17 + 194,2 Thickness

10.5 Position under load cell vs thickness of metal

Data evaluation of F max accounting for all parameters, significant or not.

Analysis of Variance

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Model	3	52,1236	95,17%	52,1236	17,3745	26,24	0,004
Linear	2	52,1235	95,17%	52,1235	26,0618	39,37	0,002
Thickness	1	52,1235	95,16%	52,1235	52,1235	78,73	0,001
Position	1	0,0000	0,00%	0,0000	0,0000	0,00	0,996
2-Way Interactions	1	0,0001	0,00%	0,0001	0,0001	0,00	0,992
Thickness*Position	1	0,0001	0,00%	0,0001	0,0001	0,00	0,992
Error	4	2,6481	4,83%	2,6481	0,6620		
Curvature	1	2,6480	4,83%	2,6480	2,6480	49936,86	0,000
Lack-of-Fit	1	0,0000	0,00%	0,0000	0,0000	0,14	0,740
Pure Error	2	0,0001	0,00%	0,0001	0,0001		
Total	7	54,7717	100,00%				

Model Summary

S	R-sq	R-sq(adj)	PRESS	R-sq(pred)
0,813653	95,17%	91,54%	23,5379	57,03%

Coded Coefficients

Term	Effect	Coef	SE Coef	95% CI	T-Value	P-Value	VIF
Constant		4,159	0,288	(3,360; 4,958)	14,46	0,000	
Thickness	7,220	3,610	0,407	(2,480; 4,739)	8,87	0,001	1,00
Position	0,003	0,002	0,288	(-0,797; 0,800)	0,01	0,996	1,00
Thickness*Position	-0,009	-0,004	0,407	(-1,134; 1,125)	-0,01	0,992	1,00

Regression Equation in Uncoded Units

F max = -6,67 + 180,5 Thickness + 0,01 Position - 0,2 Thickness*Position

Data evaluation of F max accounting only for the significant terms.

Analysis of Variance

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Model	1	52,1235	95,16%	52,1235	52,1235	118,09	0,000
Linear	1	52,1235	95,16%	52,1235	52,1235	118,09	0,000
Thickness	1	52,1235	95,16%	52,1235	52,1235	118,09	0,000
Error	6	2,6482	4,84%	2,6482	0,4414		
Curvature	1	2,6480	4,83%	2,6480	2,6480	51372,10	0,000
Lack-of-Fit	3	0,0001	0,00%	0,0001	0,0000	0,49	0,724
Pure Error	2	0,0001	0,00%	0,0001	0,0001		
Total	7	54,7717	100,00%				

Model Summary

S	R-sq	R-sq(adj)	PRESS	R-sq(pred)
0,664358	95,16%	94,36%	5,11912	90,65%

Coded Coefficients

Term	Effect	Coef	SE Coef	95% CI	T-Value	P-Value	VIF
Constant		4,159	0,235	(3,584; 4,734)	17,71	0,000	
Thickness	7,220	3,610	0,332	(2,797; 4,423)	10,87	0,000	1,00

Regression Equation in Uncoded Units

F max = -6,67 + 180,5 Thickness

10.6 Asymmetrical overhang vs thickness of metal

Data evaluation of F max accounting for all parameters, significant or not.

Analysis of Variance

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Model	3	56,5221	95,32%	56,5221	18,8407	27,15	0,004
Linear	2	56,5207	95,32%	56,5207	28,2604	40,73	0,002
Thickness	1	56,5206	95,32%	56,5206	56,5206	81,46	0,001
Position	1	0,0001	0,00%	0,0001	0,0001	0,00	0,991
2-Way Interactions	1	0,0014	0,00%	0,0014	0,0014	0,00	0,966
Thickness*Position	1	0,0014	0,00%	0,0014	0,0014	0,00	0,966
Error	4	2,7753	4,68%	2,7753	0,6938		
Curvature	1	2,7656	4,66%	2,7656	2,7656	852,77	0,000
Lack-of-Fit	1	0,0029	0,00%	0,0029	0,0029	0,85	0,454
Pure Error	2	0,0068	0,01%	0,0068	0,0034		
Total	7	59,2974	100,00%				

Model Summary

S	R-sq	R-sq(adj)	PRESS	R-sq(pred)
0,832962	95,32%	91,81%	24,6208	58,48%

Coded Coefficients

Term	Effect	Coef	SE Coef	95% CI	T-Value	P-Value	VIF
Constant		4,327	0,294	(3,510; 5,145)	14,69	0,000	
Thickness	7,518	3,759	0,416	(2,603; 4,915)	9,03	0,001	1,00
Position	0,007	0,004	0,294	(-0,814; 0,821)	0,01	0,991	1,00
Thickness*Position	-0,037	-0,019	0,416	(-1,175; 1,138)	-0,04	0,966	1,00

Regression Equation in Uncoded Units

F max = -6,95 + 188,0 Thickness + 0,06 Position - 0,9 Thickness*Position

Data evaluation of F max accounting only for the significant terms.

Analysis of Variance

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Model	1	56,5206	95,32%	56,5206	56,5206	122,13	0,000
Linear	1	56,5206	95,32%	56,5206	56,5206	122,13	0,000
Thickness	1	56,5206	95,32%	56,5206	56,5206	122,13	0,000
Error	6	2,7768	4,68%	2,7768	0,4628		
Curvature	1	2,7656	4,66%	2,7656	2,7656	1231,99	0,000
Lack-of-Fit	3	0,0044	0,01%	0,0044	0,0015	0,43	0,755
Pure Error	2	0,0068	0,01%	0,0068	0,0034		
Total	7	59,2974	100,00%				

Model Summary

S	R-sq	R-sq(adj)	PRESS	R-sq(pred)
0,680294	95,32%	94,54%	5,36363	90,95%

Coded Coefficients

Term	Effect	Coef	SE Coef	95% CI	T-Value	P-Value	VIF
Constant		4,327	0,241	(3,739; 4,916)	17,99	0,000	
Thickness	7,518	3,759	0,340	(2,927; 4,591)	11,05	0,000	1,00

Regression Equation in Uncoded Units

F max = -6,95 + 188,0 Thickness

10.7 Amount of overhang vs thickness of metal

Data evaluation of F max accounting for all parameters, significant or not.

Analysis of Variance

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Model	3	55,4284	95,41%	55,4284	18,4761	20,77	0,016
Linear	2	55,4244	95,40%	55,4244	27,7122	31,15	0,010
Thickness	1	55,4188	95,39%	55,4188	55,4188	62,30	0,004
Sample length	1	0,0056	0,01%	0,0056	0,0056	0,01	0,942
2-Way Interactions	1	0,0040	0,01%	0,0040	0,0040	0,00	0,951
Thickness*Sample length	1	0,0040	0,01%	0,0040	0,0040	0,00	0,951
Error	3	2,6685	4,59%	2,6685	0,8895		
Curvature	1	2,6678	4,59%	2,6678	2,6678	7189,78	0,000
Pure Error	2	0,0007	0,00%	0,0007	0,0004		
Total	6	58,0969	100,00%				

Model Summary

S	R-sq	R-sq(adj)	PRESS	R-sq(pred)
0,943135	95,41%	90,81%	101,673	0,00%

Coded Coefficients

Term	Effect	Coef	SE Coef	95% CI	T-Value	P-Value	VIF
Constant		4,358	0,356	(3,223; 5,492)	12,22	0,001	
Thickness	7,444	3,722	0,472	(2,221; 5,223)	7,89	0,004	1,00
Sample length	0,075	0,037	0,472	(-1,463; 1,538)	0,08	0,942	1,00
Thickness*Sample length	0,063	0,031	0,472	(-1,469; 1,532)	0,07	0,951	1,00

Regression Equation in Uncoded Units

F max = -6,68 + 182,4 Thickness - 0,019 Sample length + 0,52 Thickness*Sample length

Data evaluation of F max accounting only for the significant terms.

Analysis of Variance

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Model	1	55,4188	95,39%	55,4188	55,4188	103,47	0,000
Linear	1	55,4188	95,39%	55,4188	55,4188	103,47	0,000
Thickness	1	55,4188	95,39%	55,4188	55,4188	103,47	0,000
Error	5	2,6781	4,61%	2,6781	0,5356		
Curvature	1	2,6678	4,59%	2,6678	2,6678	1035,50	0,000
Lack-of-Fit	2	0,0096	0,02%	0,0096	0,0048	12,89	0,072
Pure Error	2	0,0007	0,00%	0,0007	0,0004		
Total	6	58,0969	100,00%				

Model Summary

S	R-sq	R-sq(adj)	PRESS	R-sq(pred)
0,731857	95,39%	94,47%	5,20351	91,04%

Coded Coefficients

Term	Effect	Coef	SE Coef	95% CI	T-Value	P-Value	VIF
Constant		4,358	0,277	(3,647; 5,069)	15,75	0,000	
Thickness	7,444	3,722	0,366	(2,782; 4,663)	10,17	0,000	1,00

Regression Equation in Uncoded Units

F max = -6,81 + 186,1 Thickness

10.8 Asymmetrical overhang vs stiffness of packaging material

Data evaluation of F max accounting for all parameters, significant or not.

Analysis of Variance

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Model	3	69,9755	99,69%	69,9755	23,3252	426,98	0,000
Linear	2	69,9328	99,63%	69,9328	34,9664	640,08	0,000
Position	1	0,1349	0,19%	0,1349	0,1349	2,47	0,191
Stiffness	1	69,7979	99,44%	69,7979	69,7979	1277,69	0,000
2-Way Interactions	1	0,0427	0,06%	0,0427	0,0427	0,78	0,427
Position*Stiffness	1	0,0427	0,06%	0,0427	0,0427	0,78	0,427
Error	4	0,2185	0,31%	0,2185	0,0546		
Curvature	1	0,1937	0,28%	0,1937	0,1937	23,41	0,017
Lack-of-Fit	1	0,0195	0,03%	0,0195	0,0195	7,28	0,114
Pure Error	2	0,0054	0,01%	0,0054	0,0027		
Total	7	70,1940	100,00%				

Model Summary

S	R-sq	R-sq(adj)	PRESS	R-sq(pred)
0,233726	99,69%	99,46%	1,90426	97,29%

Coded Coefficients

Term	Effect	Coef	SE Coef	95% CI	T-Value	P-Value	VIF
Constant		7,2544	0,0826	(7,0250; 7,4838)	87,79	0,000	
Position	0,2597	0,1299	0,0826	(-0,0996; 0,3593)	1,57	0,191	1,00
Stiffness	8,355	4,177	0,117	(3,853; 4,502)	35,74	0,000	1,00
Position*Stiffness	0,207	0,103	0,117	(-0,221; 0,428)	0,88	0,427	1,00

Regression Equation in Uncoded Units

F max = -0,636 - 0,065 Position + 0,04641 Stiffness + 0,00115 Position*Stiffness

Data evaluation of F max accounting only for the significant terms.

Analysis of Variance

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Model	1	69,7979	99,44%	69,7979	69,7979	1057,29	0,000
Linear	1	69,7979	99,44%	69,7979	69,7979	1057,29	0,000
Stiffness	1	69,7979	99,44%	69,7979	69,7979	1057,29	0,000
Error	6	0,3961	0,56%	0,3961	0,0660		
Curvature	1	0,1937	0,28%	0,1937	0,1937	4,78	0,080
Lack-of-Fit	3	0,1971	0,28%	0,1971	0,0657	24,54	0,039
Pure Error	2	0,0054	0,01%	0,0054	0,0027		
Total	7	70,1940	100,00%				

Model Summary

S	R-sq	R-sq(adj)	PRESS	R-sq(pred)
0,256936	99,44%	99,34%	0,853341	98,78%

Coded Coefficients

Term	Effect	Coef	SE Coef	95% CI	T-Value	P-Value	VIF
Constant		7,2544	0,0908	(7,0321; 7,4767)	79,86	0,000	
Stiffness	8,355	4,177	0,128	(3,863; 4,492)	32,52	0,000	1,00

Regression Equation in Uncoded Units

F max = -0,636 + 0,04641 Stiffness

10.9 Amount of overhang vs stiffness of packaging material

Data evaluation of F max accounting for all parameters, significant or not.

Analysis of Variance

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Model	3	66,0792	99,86%	66,0792	22,0264	731,06	0,000
Linear	2	66,0745	99,86%	66,0745	33,0373	1096,52	0,000
Sample length	1	0,0982	0,15%	0,0982	0,0982	3,26	0,169
Stiffness	1	65,9763	99,71%	65,9763	65,9763	2189,78	0,000
2-Way Interactions	1	0,0046	0,01%	0,0046	0,0046	0,15	0,721
Sample length*Stiffness	1	0,0046	0,01%	0,0046	0,0046	0,15	0,721
Error	3	0,0904	0,14%	0,0904	0,0301		
Curvature	1	0,0740	0,11%	0,0740	0,0740	9,02	0,095
Pure Error	2	0,0164	0,02%	0,0164	0,0082		
Total	6	66,1695	100,00%				

Model Summary

S	R-sq	R-sq(adj)	PRESS	R-sq(pred)
0,173578	99,86%	99,73%	2,84200	95,70%

Coded Coefficients

Term	Effect	Coef	SE Coef	95% CI	T-Value	P-Value	VIF
Constant		7,2080	0,0656	(6,9993; 7,4168)	109,87	0,000	
Sample length	0,3134	0,1567	0,0868	(-0,1195; 0,4329)	1,81	0,169	1,00
Stiffness	8,1226	4,0613	0,0868	(3,7851; 4,3375)	46,80	0,000	1,00
Sample length*Stiffness	0,0681	0,0341	0,0868	(-0,2421; 0,3103)	0,39	0,721	1,00

Regression Equation in Uncoded Units

F max = -0,679 + 0,00308 Sample length + 0,04424 Stiffness + 0,000013 Sample length*Stiffness

Data evaluation of F max accounting only for the significant terms.

Analysis of Variance

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Model	1	65,9763	99,71%	65,9763	65,9763	1706,87	0,000
Linear	1	65,9763	99,71%	65,9763	65,9763	1706,87	0,000
Stiffness	1	65,9763	99,71%	65,9763	65,9763	1706,87	0,000
Error	5	0,1933	0,29%	0,1933	0,0387		
Curvature	1	0,0740	0,11%	0,0740	0,0740	2,48	0,190
Lack-of-Fit	2	0,1029	0,16%	0,1029	0,0514	6,27	0,138
Pure Error	2	0,0164	0,02%	0,0164	0,0082		
Total	6	66,1695	100,00%				

Model Summary

S	R-sq	R-sq(adj)	PRESS	R-sq(pred)
0,196605	99,71%	99,65%	0,444980	99,33%

Coded Coefficients

Term	Effect	Coef	SE Coef	95% CI	T-Value	P-Value	VIF
Constant		7,2080	0,0743	(7,0170; 7,3991)	97,00	0,000	
Stiffness	8,1226	4,0613	0,0983	(3,8086; 4,3140)	41,31	0,000	1,00

Regression Equation in Uncoded Units

F max = -0,463 + 0,04513 Stiffness

10.10 Position of crease vs packaging material direction Material 1

Data evaluation of F max accounting for all parameters, significant or not.

Analysis of Variance

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Model	5	16,3453	98,88%	16,3453	3,2691	105,81	0,000
Linear	3	16,2215	98,13%	16,2215	5,4072	175,01	0,000
Position	2	0,1228	0,74%	0,1228	0,0614	1,99	0,218
Direction	1	16,0988	97,39%	16,0988	16,0988	521,05	0,000
2-Way Interactions	2	0,1238	0,75%	0,1238	0,0619	2,00	0,216
Position*Direction	2	0,1238	0,75%	0,1238	0,0619	2,00	0,216
Error	6	0,1854	1,12%	0,1854	0,0309		
Total	11	16,5307	100,00%				

Model Summary

S	R-sq	R-sq(adj)	PRESS	R-sq(pred)
0,175775	98,88%	97,94%	0,741522	95,51%

Coefficients

Term	Coef	SE Coef	95% CI	T-Value	P-Value	VIF
Constant	6,9209	0,0507	(6,7967; 7,0451)	136,39	0,000	
Position						
0%	-0,0378	0,0718	(-0,2134; 0,1378)	-0,53	0,618	1,33
50%	-0,1006	0,0718	(-0,2762; 0,0750)	-1,40	0,210	1,33
100%	0,1384	0,0718	(-0,0372; 0,3140)	1,93	0,102	*
Direction						
MD	-1,1583	0,0507	(-1,2824; -1,0341)	-22,83	0,000	1,00
CD	1,1583	0,0507	(1,0341; 1,2824)	22,83	0,000	*
Position*Direction						
0% MD	0,0377	0,0718	(-0,1379; 0,2133)	0,52	0,618	1,33
0% CD	-0,0377	0,0718	(-0,2133; 0,1379)	-0,52	0,618	*
50% MD	0,1012	0,0718	(-0,0744; 0,2768)	1,41	0,208	1,33
50% CD	-0,1012	0,0718	(-0,2768; 0,0744)	-1,41	0,208	*
100% MD	-0,1389	0,0718	(-0,3145; 0,0367)	-1,94	0,101	*
100% CD	0,1389	0,0718	(-0,0367; 0,3145)	1,94	0,101	*

Regression Equation

F max = 6,9209 - 0,0378 Position_0% - 0,1006 Position_50% + 0,1384 Position_100%
- 1,1583 Direction_MD + 1,1583 Direction_CD + 0,0377 Position*Direction_0% MD
- 0,0377 Position*Direction_0% CD + 0,1012 Position*Direction_50% MD
- 0,1012 Position*Direction_50% CD - 0,1389 Position*Direction_100% MD
+ 0,1389 Position*Direction_100% CD

Data evaluation of F max accounting only for the significant terms.

Analysis of Variance

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Model	1	16,0988	97,39%	16,0988	16,0988	372,68	0,000
Linear	1	16,0988	97,39%	16,0988	16,0988	372,68	0,000
Direction	1	16,0988	97,39%	16,0988	16,0988	372,68	0,000
Error	10	0,4320	2,61%	0,4320	0,0432		
Lack-of-Fit	4	0,2466	1,49%	0,2466	0,0616	2,00	0,214
Pure Error	6	0,1854	1,12%	0,1854	0,0309		
Total	11	16,5307	100,00%				

Model Summary

S	R-sq	R-sq(adj)	PRESS	R-sq(pred)
0,207839	97,39%	97,13%	0,622038	96,24%

Coefficients

Term	Coef	SE Coef	95% CI	T-Value	P-Value	VIF
Constant	6,9209	0,0600	(6,7872; 7,0546)	115,35	0,000	
Direction						
MD	-1,1583	0,0600	(-1,2919; -1,0246)	-19,30	0,000	1,00
CD	1,1583	0,0600	(1,0246; 1,2919)	19,30	0,000	*

Regression Equation

F max = 6,9209 - 1,1583 Direction_MD + 1,1583 Direction_CD

Fits and Diagnostics for Unusual Observations

Obs	F max	Fit	SE Fit	95% CI	Resid	Std Resid	Del Resid	HI	Cook's D
1	8,5848	8,0792	0,0848	(7,8901; 8,2682)	0,5056	2,66	4,70	0,166667	0,71

Obs	DFITS	
1	2,10022	R

R Large residual

Data evaluation of compression distance at F max accounting for all parameters, significant or not.

Analysis of Variance

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Model	5	5,81597	99,10%	5,81597	1,16319	132,41	0,000
Linear	3	5,72581	97,57%	5,72581	1,90860	217,27	0,000
Position	2	0,04690	0,80%	0,04690	0,02345	2,67	0,148
Direction	1	5,67891	96,77%	5,67891	5,67891	646,47	0,000
2-Way Interactions	2	0,09016	1,54%	0,09016	0,04508	5,13	0,050
Position*Direction	2	0,09016	1,54%	0,09016	0,04508	5,13	0,050
Error	6	0,05271	0,90%	0,05271	0,00878		
Total	11	5,86868	100,00%				

Model Summary

S	R-sq	R-sq(adj)	PRESS	R-sq(pred)
0,0937257	99,10%	98,35%	0,210828	96,41%

Coefficients

Term	Coef	SE Coef	95% CI	T-Value	P-Value	VIF
Constant	2,3742	0,0271	(2,3080; 2,4404)	87,75	0,000	
Position						
0%	-0,0843	0,0383	(-0,1779; 0,0093)	-2,20	0,070	1,33
50%	0,0191	0,0383	(-0,0746; 0,1127)	0,50	0,636	1,33
100%	0,0652	0,0383	(-0,0284; 0,1589)	1,70	0,139	*
Direction						
MD	0,6879	0,0271	(0,6217; 0,7541)	25,43	0,000	1,00
CD	-0,6879	0,0271	(-0,7541; -0,6217)	-25,43	0,000	*
Position*Direction						
0% MD	0,0045	0,0383	(-0,0891; 0,0981)	0,12	0,910	1,33
0% CD	-0,0045	0,0383	(-0,0981; 0,0891)	-0,12	0,910	*
50% MD	0,1038	0,0383	(0,0102; 0,1975)	2,71	0,035	1,33
50% CD	-0,1038	0,0383	(-0,1975; -0,0102)	-2,71	0,035	*
100% MD	-0,1083	0,0383	(-0,2020; -0,0147)	-2,83	0,030	*
100% CD	0,1083	0,0383	(0,0147; 0,2020)	2,83	0,030	*

Regression Equation

Compression at F max = 2,3742 - 0,0843 Position_0% + 0,0191 Position_50%
+ 0,0652 Position_100% + 0,6879 Direction_MD - 0,6879 Direction_CD
+ 0,0045 Position*Direction_0% MD - 0,0045 Position*Direction_0% CD
+ 0,1038 Position*Direction_50% MD - 0,1038 Position*Direction_50% CD
- 0,1083 Position*Direction_100% MD + 0,1083 Position*Direction_100%
CD

Data evaluation of compression distance at F max accounting only for the significant terms.

Analysis of Variance

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Model	1	5,67891	96,77%	5,67891	5,67891	299,26	0,000
Linear	1	5,67891	96,77%	5,67891	5,67891	299,26	0,000
Direction	1	5,67891	96,77%	5,67891	5,67891	299,26	0,000
Error	10	0,18977	3,23%	0,18977	0,01898		
Lack-of-Fit	4	0,13706	2,34%	0,13706	0,03426	3,90	0,068
Pure Error	6	0,05271	0,90%	0,05271	0,00878		
Total	11	5,86868	100,00%				

Model Summary

S	R-sq	R-sq(adj)	PRESS	R-sq(pred)
0,137756	96,77%	96,44%	0,273264	95,34%

Coefficients

Term	Coef	SE Coef	95% CI	T-Value	P-Value	VIF
Constant	2,3742	0,0398	(2,2856; 2,4628)	59,70	0,000	
Direction						
MD	0,6879	0,0398	(0,5993; 0,7765)	17,30	0,000	1,00
CD	-0,6879	0,0398	(-0,7765; -0,5993)	-17,30	0,000	*

Regression Equation

Compression at F max = 2,3742 + 0,6879 Direction_MD - 0,6879 Direction_CD

10.11 Position of crease vs packaging material direction Material 2

Data evaluation accounting for all parameters, significant or not.

Analysis of Variance

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Model	5	19,8894	99,39%	19,8894	3,9779	194,25	0,000
Linear	3	19,8762	99,32%	19,8762	6,6254	323,54	0,000
Position	2	0,1222	0,61%	0,1222	0,0611	2,98	0,126
Direction	1	19,7540	98,71%	19,7540	19,7540	964,65	0,000
2-Way Interactions	2	0,0132	0,07%	0,0132	0,0066	0,32	0,737
Position*Direction	2	0,0132	0,07%	0,0132	0,0066	0,32	0,737
Error	6	0,1229	0,61%	0,1229	0,0205		
Total	11	20,0123	100,00%				

Model Summary

S	R-sq	R-sq(adj)	PRESS	R-sq(pred)
0,143101	99,39%	98,87%	0,491468	97,54%

Coefficients

Term	Coef	SE Coef	95% CI	T-Value	P-Value	VIF
Constant	6,9657	0,0413	(6,8646; 7,0668)	168,62	0,000	
Position						
0%	-0,1286	0,0584	(-0,2716; 0,0143)	-2,20	0,070	1,33
50%	0,0107	0,0584	(-0,1322; 0,1537)	0,18	0,860	1,33
100%	0,1179	0,0584	(-0,0251; 0,2608)	2,02	0,090	*
Direction						
MD	-1,2830	0,0413	(-1,3841; -1,1819)	-31,06	0,000	1,00
CD	1,2830	0,0413	(1,1819; 1,3841)	31,06	0,000	*
Position*Direction						
0% MD	0,0433	0,0584	(-0,0996; 0,1863)	0,74	0,486	1,33
0% CD	-0,0433	0,0584	(-0,1863; 0,0996)	-0,74	0,486	*
50% MD	-0,0062	0,0584	(-0,1492; 0,1367)	-0,11	0,918	1,33
50% CD	0,0062	0,0584	(-0,1367; 0,1492)	0,11	0,918	*
100% MD	-0,0371	0,0584	(-0,1800; 0,1059)	-0,63	0,549	*
100% CD	0,0371	0,0584	(-0,1059; 0,1800)	0,63	0,549	*

Regression Equation

F max = 6,9657 - 0,1286 Position_0% + 0,0107 Position_50% + 0,1179 Position_100%
- 1,2830 Direction_MD + 1,2830 Direction_CD + 0,0433 Position*Direction_0% MD
- 0,0433 Position*Direction_0% CD - 0,0062 Position*Direction_50% MD
+ 0,0062 Position*Direction_50% CD - 0,0371 Position*Direction_100% MD
+ 0,0371 Position*Direction_100% CD

Data evaluation of F max accounting only for the significant terms.

Analysis of Variance

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Model	1	19,7540	98,71%	19,7540	19,7540	764,86	0,000
Linear	1	19,7540	98,71%	19,7540	19,7540	764,86	0,000
Direction	1	19,7540	98,71%	19,7540	19,7540	764,86	0,000
Error	10	0,2583	1,29%	0,2583	0,0258		
Lack-of-Fit	4	0,1354	0,68%	0,1354	0,0339	1,65	0,277
Pure Error	6	0,1229	0,61%	0,1229	0,0205		
Total	11	20,0123	100,00%				

Model Summary

S	R-sq	R-sq(adj)	PRESS	R-sq(pred)
0,160708	98,71%	98,58%	0,371909	98,14%

Coefficients

Term	Coef	SE Coef	95% CI	T-Value	P-Value	VIF
Constant	6,9657	0,0464	(6,8623; 7,0691)	150,15	0,000	
Direction						
MD	-1,2830	0,0464	(-1,3864; -1,1797)	-27,66	0,000	1,00
CD	1,2830	0,0464	(1,1797; 1,3864)	27,66	0,000	*

Regression Equation

F max = 6,9657 - 1,2830 Direction_MD + 1,2830 Direction_CD

Data evaluation of compression distance at F max accounting for all parameters, significant or not.

Analysis of Variance

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Model	5	4,63811	98,71%	4,63811	0,92762	91,69	0,000
Linear	3	4,55690	96,98%	4,55690	1,51897	150,13	0,000
Position	2	0,00545	0,12%	0,00545	0,00273	0,27	0,773
Direction	1	4,55145	96,86%	4,55145	4,55145	449,86	0,000
2-Way Interactions	2	0,08121	1,73%	0,08121	0,04060	4,01	0,078
Position*Direction	2	0,08121	1,73%	0,08121	0,04060	4,01	0,078
Error	6	0,06070	1,29%	0,06070	0,01012		
Total	11	4,69881	100,00%				

Model Summary

S	R-sq	R-sq(adj)	PRESS	R-sq(pred)
0,100585	98,71%	97,63%	0,242818	94,83%

Coefficients

Term	Coef	SE Coef	95% CI	T-Value	P-Value	VIF
Constant	2,8722	0,0290	(2,8012; 2,9433)	98,92	0,000	
Position						
0%	0,0231	0,0411	(-0,0774; 0,1236)	0,56	0,594	1,33
50%	-0,0283	0,0411	(-0,1288; 0,0722)	-0,69	0,516	1,33
100%	0,0052	0,0411	(-0,0953; 0,1057)	0,13	0,903	*
Direction						
MD	0,6159	0,0290	(0,5448; 0,6869)	21,21	0,000	1,00
CD	-0,6159	0,0290	(-0,6869; -0,5448)	-21,21	0,000	*
Position*Direction						
0% MD	0,0758	0,0411	(-0,0247; 0,1763)	1,85	0,114	1,33
0% CD	-0,0758	0,0411	(-0,1763; 0,0247)	-1,85	0,114	*
50% MD	0,0385	0,0411	(-0,0620; 0,1390)	0,94	0,384	1,33
50% CD	-0,0385	0,0411	(-0,1390; 0,0620)	-0,94	0,384	*
100% MD	-0,1143	0,0411	(-0,2148; -0,0139)	-2,78	0,032	*
100% CD	0,1143	0,0411	(0,0139; 0,2148)	2,78	0,032	*

Regression Equation

Distance to F max = 2,8722 + 0,0231 Position_0% - 0,0283 Position_50% + 0,0052 Position_100%
+ 0,6159 Direction_MD - 0,6159 Direction_CD
+ 0,0758 Position*Direction_0% MD - 0,0758 Position*Direction_0% CD
+ 0,0385 Position*Direction_50% MD - 0,0385 Position*Direction_50% CD
- 0,1143 Position*Direction_100% MD + 0,1143 Position*Direction_100% CD

Data evaluation of compression distance at F max accounting only for the significant terms.

Analysis of Variance

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Model	1	4,55145	96,86%	4,55145	4,55145	308,86	0,000
Linear	1	4,55145	96,86%	4,55145	4,55145	308,86	0,000
Direction	1	4,55145	96,86%	4,55145	4,55145	308,86	0,000
Error	10	0,14736	3,14%	0,14736	0,01474		
Lack-of-Fit	4	0,08666	1,84%	0,08666	0,02166	2,14	0,193
Pure Error	6	0,06070	1,29%	0,06070	0,01012		
Total	11	4,69881	100,00%				

Model Summary

S	R-sq	R-sq(adj)	PRESS	R-sq(pred)
0,121393	96,86%	96,55%	0,212203	95,48%

Coefficients

Term	Coef	SE Coef	95% CI	T-Value	P-Value	VIF
Constant	2,8722	0,0350	(2,7942; 2,9503)	81,96	0,000	
Direction						
MD	0,6159	0,0350	(0,5378; 0,6939)	17,57	0,000	1,00
CD	-0,6159	0,0350	(-0,6939; -0,5378)	-17,57	0,000	*

Regression Equation

Distance to F max = 2,8722 + 0,6159 Direction_MD - 0,6159 Direction_CD

10.12 Position of crease vs packaging material direction Material 3

Data evaluation of F max accounting for all parameters, significant or not.

Analysis of Variance

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Model	5	69,4598	99,95%	69,4598	13,8920	2300,44	0,000
Linear	3	67,3273	96,88%	67,3273	22,4424	3716,35	0,000
Position	2	4,9407	7,11%	4,9407	2,4704	409,08	0,000
Direction	1	62,3866	89,77%	62,3866	62,3866	10330,90	0,000
2-Way Interactions	2	2,1325	3,07%	2,1325	1,0663	176,57	0,000
Position*Direction	2	2,1325	3,07%	2,1325	1,0663	176,57	0,000
Error	6	0,0362	0,05%	0,0362	0,0060		
Total	11	69,4960	100,00%				

Model Summary

S	R-sq	R-sq(adj)	PRESS	R-sq(pred)
0,0777099	99,95%	99,90%	0,144932	99,79%

Coefficients

Term	Coef	SE Coef	95% CI	T-Value	P-Value	VIF
Constant	13,3738	0,0224	(13,3189; 13,4287)	596,17	0,000	
Position						
0%	-0,5985	0,0317	(-0,6761; -0,5208)	-18,86	0,000	1,33
50%	-0,2915	0,0317	(-0,3691; -0,2139)	-9,19	0,000	1,33
100%	0,8900	0,0317	(0,8123; 0,9676)	28,05	0,000	*
Direction						
MD	-2,2801	0,0224	(-2,3350; -2,2252)	-101,64	0,000	1,00
CD	2,2801	0,0224	(2,2252; 2,3350)	101,64	0,000	*
Position*Direction						
0% MD	0,4436	0,0317	(0,3660; 0,5213)	13,98	0,000	1,33
0% CD	-0,4436	0,0317	(-0,5213; -0,3660)	-13,98	0,000	*
50% MD	0,1231	0,0317	(0,0455; 0,2007)	3,88	0,008	1,33
50% CD	-0,1231	0,0317	(-0,2007; -0,0455)	-3,88	0,008	*
100% MD	-0,5667	0,0317	(-0,6444; -0,4891)	-17,86	0,000	*
100% CD	0,5667	0,0317	(0,4891; 0,6444)	17,86	0,000	*

Regression Equation

F max = 13,3738 - 0,5985 Position_0% - 0,2915 Position_50% + 0,8900 Position_100%
- 2,2801 Direction_MD + 2,2801 Direction_CD + 0,4436 Position*Direction_0% MD
- 0,4436 Position*Direction_0% CD + 0,1231 Position*Direction_50% MD
- 0,1231 Position*Direction_50% CD - 0,5667 Position*Direction_100% MD
+ 0,5667 Position*Direction_100% CD

Data evaluation of compression distance at F max accounting for all parameters, significant or not.

Analysis of Variance

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Model	5	5,16927	99,84%	5,16927	1,03385	747,70	0,000
Linear	3	5,15944	99,65%	5,15944	1,71981	1243,80	0,000
Position	2	0,17379	3,36%	0,17379	0,08689	62,84	0,000
Direction	1	4,98566	96,29%	4,98566	4,98566	3605,71	0,000
2-Way Interactions	2	0,00982	0,19%	0,00982	0,00491	3,55	0,096
Position*Direction	2	0,00982	0,19%	0,00982	0,00491	3,55	0,096
Error	6	0,00830	0,16%	0,00830	0,00138		
Total	11	5,17756	100,00%				

Model Summary

S	R-sq	R-sq(adj)	PRESS	R-sq(pred)
0,0371848	99,84%	99,71%	0,0331851	99,36%

Coefficients

Term	Coef	SE Coef	95% CI	T-Value	P-Value	VIF
Constant	2,2746	0,0107	(2,2483; 2,3008)	211,90	0,000	
Position						
0%	-0,1209	0,0152	(-0,1580; -0,0837)	-7,96	0,000	1,33
50%	-0,0433	0,0152	(-0,0805; -0,0062)	-2,85	0,029	1,33
100%	0,1642	0,0152	(0,1271; 0,2013)	10,82	0,000	*
Direction						
MD	0,6446	0,0107	(0,6183; 0,6708)	60,05	0,000	1,00
CD	-0,6446	0,0107	(-0,6708; -0,6183)	-60,05	0,000	*
Position*Direction						
0% MD	0,0155	0,0152	(-0,0217; 0,0526)	1,02	0,348	1,33
0% CD	-0,0155	0,0152	(-0,0526; 0,0217)	-1,02	0,348	*
50% MD	0,0247	0,0152	(-0,0125; 0,0618)	1,62	0,155	1,33
50% CD	-0,0247	0,0152	(-0,0618; 0,0125)	-1,62	0,155	*
100% MD	-0,0401	0,0152	(-0,0773; -0,0030)	-2,64	0,038	*
100% CD	0,0401	0,0152	(0,0030; 0,0773)	2,64	0,038	*

Regression Equation

Compression at F max = 2,2746 - 0,1209 Position_0% - 0,0433 Position_50%
+ 0,1642 Position_100% + 0,6446 Direction_MD - 0,6446 Direction_CD
+ 0,0155 Position*Direction_0% MD - 0,0155 Position*Direction_0% CD
+ 0,0247 Position*Direction_50% MD - 0,0247 Position*Direction_50% CD
- 0,0401 Position*Direction_100% MD + 0,0401 Position*Direction_100%
CD

Data evaluation of compression distance at F max accounting only for the significant terms.

Analysis of Variance

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Model	3	5,15944	99,65%	5,15944	1,71981	759,27	0,000
Linear	3	5,15944	99,65%	5,15944	1,71981	759,27	0,000
Position	2	0,17379	3,36%	0,17379	0,08689	38,36	0,000
Direction	1	4,98566	96,29%	4,98566	4,98566	2201,07	0,000
Error	8	0,01812	0,35%	0,01812	0,00227		
Lack-of-Fit	2	0,00982	0,19%	0,00982	0,00491	3,55	0,096
Pure Error	6	0,00830	0,16%	0,00830	0,00138		
Total	11	5,17756	100,00%				

Model Summary

S	R-sq	R-sq(adj)	PRESS	R-sq(pred)
0,0475931	99,65%	99,52%	0,0407718	99,21%

Coefficients

Term	Coef	SE Coef	95% CI	T-Value	P-Value	VIF
Constant	2,2746	0,0137	(2,2429; 2,3063)	165,56	0,000	
Position						
0%	-0,1209	0,0194	(-0,1657; -0,0761)	-6,22	0,000	1,33
50%	-0,0433	0,0194	(-0,0881; 0,0015)	-2,23	0,056	1,33
100%	0,1642	0,0194	(0,1194; 0,2090)	8,45	0,000	*
Direction						
MD	0,6446	0,0137	(0,6129; 0,6763)	46,92	0,000	1,00
CD	-0,6446	0,0137	(-0,6763; -0,6129)	-46,92	0,000	*

Regression Equation

Compression at F max = 2,2746 - 0,1209 Position_0% - 0,0433 Position_50%
+ 0,1642 Position_100% + 0,6446 Direction_MD - 0,6446 Direction_CD

10.13 Folding direction vs stiffness of packaging material

Data evaluation of F max accounting for all parameters.

Analysis of Variance

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Model	5	63,6889	99,91%	63,6889	12,7378	1370,44	0,000
Linear	3	60,6454	95,14%	60,6454	20,2151	2174,92	0,000
Folding Direction	1	7,2185	11,32%	7,2185	7,2185	776,63	0,000
Material	2	53,4269	83,81%	53,4269	26,7135	2874,07	0,000
2-Way Interactions	2	3,0435	4,77%	3,0435	1,5218	163,72	0,000
Folding Direction*Material	2	3,0435	4,77%	3,0435	1,5218	163,72	0,000
Error	6	0,0558	0,09%	0,0558	0,0093		
Total	11	63,7447	100,00%				

Model Summary

S	R-sq	R-sq(adj)	PRESS	R-sq(pred)
0,0964088	99,91%	99,84%	0,223072	99,65%

Coefficients

Term	Coef	SE Coef	95% CI	T-Value	P-Value	VIF
Constant	6,8166	0,0278	(6,7485; 6,8847)	244,93	0,000	
Folding Direction						
Inside Inside	-0,7756	0,0278	(-0,8437; -0,7075)	-27,87	0,000	1,00
Outside Outside	0,7756	0,0278	(0,7075; 0,8437)	27,87	0,000	*
Material						
Material 1	-1,3398	0,0394	(-1,4361; -1,2435)	-34,04	0,000	1,33
Material 2	-1,6392	0,0394	(-1,7355; -1,5429)	-41,65	0,000	1,33
Material 3	2,9790	0,0394	(2,8827; 3,0753)	75,69	0,000	*
Folding Direction*Material						
Inside Inside Material 1	0,5159	0,0394	(0,4196; 0,6122)	13,11	0,000	1,33
Inside Inside Material 2	0,1673	0,0394	(0,0710; 0,2636)	4,25	0,005	1,33
Inside Inside Material 3	-0,6832	0,0394	(-0,7795; -0,5869)	-17,36	0,000	*
Outside Outside Material 1	-0,5159	0,0394	(-0,6122; -0,4196)	-13,11	0,000	*
Outside Outside Material 2	-0,1673	0,0394	(-0,2636; -0,0710)	-4,25	0,005	*
Outside Outside Material 3	0,6832	0,0394	(0,5869; 0,7795)	17,36	0,000	*

Regression Equation

F max = 6,8166 - 0,7756 Folding Direction_Inside Inside + 0,7756 Folding Direction_Outside Outside - 1,3398 Material_Material 1 - 1,6392 Material_Material 2
+ 2,9790 Material_Material 3 + 0,5159 Folding Direction*Material_Inside Inside Material 1 + 0,1673 Folding Direction*Material_Inside Inside Material 2
- 0,6832 Folding Direction*Material_Inside Inside Material 3
- 0,5159 Folding Direction*Material_Outside Outside Material 1
- 0,1673 Folding Direction*Material_Outside Outside Material 2
+ 0,6832 Folding Direction*Material_Outside Outside Material 3