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Master Thesis

Investigation of mechanical tearing

- and how it can be applied in package openability prediction

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Abstract

Perforations are one of Tetra Pak's oldest inventions of how to open their carton packages. They have been a part of Tetra Brik's product portfolio for over 30 years and quality testing is important. Bad openability, with plastic residues covering the torn hole, is a problem that needs to be addressed.

When tearing a package with perforation all people do it differently. By using a mechanical tearing method during testing it is possible to reduce this variation. A method like this is developed but it is not used widely and its results are often not satisfactory. The aim for this work is to investigate tearing done with this method. What to measure and how measured results are changed by material parameters affecting the openability.

The practical part of this work is divided into two parts. The first is qualitative tests with the goal to increase the knowledge of the measuring procedure and its resulting energy curve. How is the board breaking? What energies, forces etc. should be measured to be able to extract as much valuable information as possible. The second part has a quantitative approach, to correlate the energy measurements with openability results, by measuring tearing energy on folded packaging material. This part also evaluates the method itself and which measured response's that are best to use to describe the openability problem.

The results show that when using the mechanical tearing method one uses out-of- plane shear forces to break the perforation. The total energy during tearing is the best and most robust response to use if one wants to correlate tearing energy with openability. Material and process parameters that affect measured Total energy as well as the openability are the knife type, perforation engagement, and polymer grammage of the inside polymer layer. The variation in results during measurements, caused either by the equipment or the material, needs to be lowered as the method shows poor repeatability. It is most likely possible to develop a new or enhance the existing method to focus on tearing energy to perform test on perforations and predict issues with openability.

Acknowledgement

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Lund in January 2009

Henrik Skanse

Table of content

1 Introduction

This chapter introduces the reader to this work as well as Tetra Pak and its business.

1.1 Background

Over 50 years ago the story of Tetra Pak began when the company was set up by Dr Ruben Rausing. He had been visiting the United States, were he saw the first supermarkets taking shape, and he understood the need of offering milk and other fresh beverages as an of the shelf product[1]. At this time milk was mainly distributed in glass bottles and could not be kept fresh for long time. The name Tetra Pak came from the first invention done by Erik Wallenberg,[2] which was a very cost effective package formed as a tetrahedron, later becoming the Tetra Classic. This shape is the most efficient regarding minimum material and maximum volume and together with the roll fed filling procedure they had created a very cost competitive package solution.
1961 when the aseptic packaging technology first was introduced it was a breakthrough for beverage packaging. It gave the industry a whole new dimension as packages could be sterilized and packed to last and stay fresh for a longer time period. Since then the company have gone through a lot of changes and many concepts have been developed and emerged from the first tetrahedron design but Tetra Pak continues to be the market leader in beverages packaging in carton packages.

Tetra Pak Group is now one of three part of Tetra Laval Group together with the bottle company Sidel and De Laval who produces diary farming equipment.

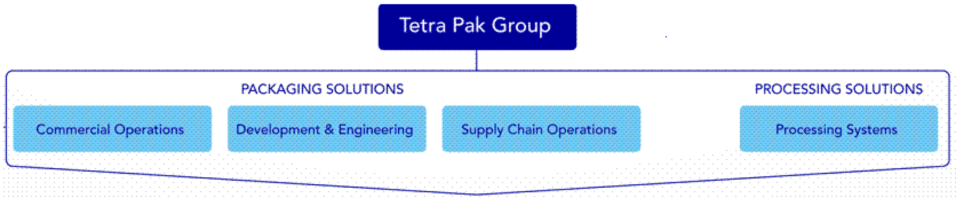

Figure 1 – Organisation

Tetra Pak Packaging Solutions develops new packaging platforms, packaging material, and material converting processes. The filling machines are sold and then located at the customer site, e.g. a diary or juice producer. This is where all the packages are produced and filled before they reach the stores and the

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[1] Tetra Pak – Development in brief
[2] Tetra Pak – Development in brief

hands of us end users, the consumers. To be able to run these filling machines Tetra Pak sells packaging material that consists of printed carton board, often together with aluminum foil, that are laminated with a mix of polymers.

Tetra Pak's product portfolio consists of packages in many different shapes and volumes and they are divided in two main categories, aseptic and pasteurized. They differ in several ways as material structure, filling procedure and liquid level in the packages. The benefit of the Aseptic technology is that you are able to pack beverages so that they can stay fresh for a much longer time, up to 12 months. It is achieved by using higher temperature and airtight technology during the filling process, including aluminum in the material as a light barrier, and increasing the liquid level in the packages not allowing for headspace.

Figure 2 – A part of the product portfolio

Ever since the first packages where designed and produced openings have been a critical part of their function. It does not matter how good you protect the liquid from the outside or how long it can last on the shelf if you can not get it out and consume it in a convenient way. To open the first tetrahedron shaped package you had to be equipped with a pair of scissor if it did not come with straws. It was not until 15 years after the launch of Tetra Brik, mid seventies, the perforation was launched as an opening and then you could open the packages by hand. To open a perforation opening you tear along the direction of a perforated line and achieve an opening in one top corner and can then pour the content in for example a glass.

Figure 3 - Tearing of Tetra Brik

Many new openings and especially screw caps have seen the light in later years and they are very appreciated by both Tetra Pak's customers and the consumers. Re-sealable screw caps have set a new standard regarding openability of carton packages and it is an important development for Tetra Pak to be able to keep up with plastic-bottle competitors and their advantages. Even if many of the consumers have taken the screw caps to their heart and expect it to be a standard opening at this time the perforation is still chosen by many diary customers due to the low cost and unbeatable ability to stack packages very efficient.

1.2 Problem identifier

As long as perforations are a substantial part of the Tetra Brik Aseptic product portfolio there is a demand for quality testing and understanding of the opening procedure. Tetra Pak wants to deliver a package that does not give problems when consumers tear along the perforation regardless of if they pre-fold it, use right or left hand, changing tearing direction etc. It is not hard to understand that the "right" way to open does not exist and with this in mind the only way to look at it from a company perspective is for Tetra Pak to say that consumers always do the right thing and the design should be good enough to cope with these variations.

Even if there is no perfect way of opening a package there is a need to do quality measurements. These are now done by human hands but due to the variations of people's openings procedures these results are very hard to compare and analyze. To be able to compare different material qualities there is a need for a mechanical method with less human influence. During 2004 this problem was addressed and the package laboratory in Modena, Italy, tried to develop a test rig that tears the perforation as it could have been done by humans but in the same way every time. This was developed after studying hours of film from panel tests with consumers opening perforated packages. The result of this work is a test method which is used to measure the initial peak load corresponding to the force a consumer has to apply to be able to crack the first part of the board and start the tearing. The measurements from the method result in more than this peak load and an energy curve of the lapse is given. Can this curve tell us more about the opening quality than what is known today and could it become a good way to measure and rank packaging material as most of the human variations during tearing can be excluded. When discussing this possibility the lack of understanding of the process and its result are always mentioned and without that the right information is hard to extract out of the collected data.

1.3 Objective

The goal of this work is firstly to increase the knowledge about the mechanical tearing procedure in terms of what phenomenon that is possible to measure and how they corresponds to the energy curve?

Secondly the work will show if tearing energy absorption is a possible theory to base a test method on that correlates with the package performance regarding openability. In order to fulfill the goal of this thesis certain questions need to be answered:

- How the remaining parts of the carton board along the perforation are cracked, is it by tensile or tear breakage?
- Is it possible to distinguish between different packaging materials regarding openability by using mechanical tearing?

1.4 Research focus

This work will focus on the mechanical tearing procedure. It will describe the tearing process regarding forces and energy curve to be able to increase the understanding of the process. Mechanical tearing procedure will be used to be able to exclude the influence that peoples varying opening strategy have on both the lapse and the result. Straight angled perforation from portion packs will be used which is one of four different perforations. Together with my supervisor this is chosen because there is packaging material to use and because it has a consistent distance between the knife's teeth. All measurements will be made on folded packaging material even if there at this stage is not any proved correlation between packaging material results and the package openability.

1.5 Target group

The aim for this work is to be a broad investigation and increase people's knowledge about perforation testing and openability problems. One looks at the openability issue from a packaging material and converting perspective to see how material should be tested and optimized to reduce plastic residues. The future readers will be people involved in perforation quality testing within Packaging Technology, Carton Economy, and Carton Value. The work can also be interesting for people working within converting specifications and converting processes.

2 Methodology

This chapter describes the importance of choosing a methodology and explains how the work will benefit by using different methodology approaches.

2.1 Different approaches

Constant evolving of our knowledge and capacity is something that drives us humans forward in life. This is mainly done by research and its importance should not be forgotten. The research process is divided in three main forms that differ in aim and procedure. The lines separating these 3 are not very distinctive and rather a little bit vague but they are[3]:

- **Exploratory research**, which structures new problems.
- **Constructive research,** which develops solutions to known problems
- **Empirical research,** which evaluate the feasibility of a solution with empirical evidence's.

2.1.1 Exploratory research

This kind of approach is neither a problem solver nor decision making tool[4]. Instead it is used to get a significant insight into problems and their nature. It is definitely the best way to start when you want to bring light to a problem and investigate the extent of it. To do exploratory research before you come up with the formulation of a problem is very useful and will make the following work easier.

2.1.2 Constructive research

This type of research is the kind of research that comes up with solutions. Compared to other methods empirical evidences are not necessary to prove the research[5]. Instead benchmarking can be a good tool to be able to compare the solution with a reference. The solution should not contain too much logic and should instead have an objective foundation.

2.1.3 Empirical research

Empirical research is used when one wants to prove theories or visualize phenomenon. It can contain interviews, destructive tests or only observations. The researcher has to be aware of the importance of choosing samples or respondents which can really question the results. The hypothetico-deductive

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[3] www.nationmaster.com/encyclopedia/Pure-research#Research_methods, (2008-09-16)
[4] www.researchxl.com/methods/exploratory, (2008-10-03)
[5] www.researchxl.com/methods/constructive, (2008-10-03)

method that was introduced by Karl Popper (1902-1994) says that a hypothesis is true until falsification[6]. He stated that a theory within this method should include what is not allowed to happen to keep the theory valid.

2.1.4 Choosing approach

What type of research you are doing is an important knowledge to be able to formulate your problem and find the best way to achieve the intended goals.
This master thesis will begin as an exploratory research to get a better understanding of a process and will then terminate in an empirical research to evaluate the theory rather than a solution.

The problem with plastic residues needs a solution which would push for a constructive research approach, with a solution to the plastic residues as the goal. As the thesis only look at a limited part of the problem which can be valuable during further investigations and attempts to solve the plastic residues problem a constructive approach will not be used.

2.2 Qualitative and Quantitative methods

One can use different approaches in research and the methodology dilemma is often ending up in the discussion of quantitative versus qualitative research. It is important to understand the differences to be able to choose the method that suits your identified problem and contribute the most to the desired solution[7]. If an unsuitable method is chosen the validity of the results can be challenged. Interviews and case studies are also possible approaches that can be used. They are very important tools if you want to find the problem or deal with how it appears. Case studies are a qualitative tool and interviews can be both qualitative and quantitative depending on how they are performed. In this research this is information that is already known and these methods are not necessary.

2.2.1 Qualitative research

Qualitative research is often done to achieve a deeper understanding of a process or procedure. As a researcher you collect information to support this goal and tests are often characterized by the presence of the researchers and how they are allowed to adjust tests along the way to achieve as valuable and information rich results as possible[8]. A test is seen as an information source and adjustments along the way are important to extract as much information as possible from it. Even if validation of the results is not the main goal this is often questioned when a qualitative approach is used. This is a reason why it is very important to always take notes of changes made during tests to be able to

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[6] www.researchxl.com/methods/empirical (2008-10-03)
[7] Forskningsmetodik (1997)
[8] Forskningsmetodik (1997)

backtrack and know which circumstances each test had. Due to the near presence of the researcher there is a high risk that his prior knowledge, thoughts, or presence interfere the results in an undesirable way[9].

2.2.2 Quantitative research

Quantitative research is known to be stricter than the qualitative. Its main goal is to compare and prove results and it is often the difference that is most important. To find and define interesting relations with the objectives in mind a structured research planning is used already during the early stage. Data analyses are done by using statistical methods and design of experiments is an important phase not to forget to be successful[10]. Statistical methods are often using numbers and when using quantitative research you have to be able to describe qualitative phenomenon quantitatively by these number. In some research areas this can be hard but in natural science results often come in numbers after measuring magnitudes as forces, energies, distances etc. A problem can be that people have too much confidence in numbers and think that if something is measured in numbers it must be right[11]. It is important to keep in mind that data does not get better by using statistical methods and data will not give better or more information just because the analysis was done with an additional statistical tool.

2.2.3 Theory or model

Theory or model, what is the difference? Theories are supposed to increase the knowledge of the reality and not describe how the reality works[12]. It is a simplified reflection of the reality and it is formed by many connecting hypothesis. A model is the next step after having a theory. A model is built on a theory but it has to be much more detailed and specific. In contrast with the theory a model should describe the reality and the more complex model there is the more it will emulate the real phenomenon. How different parts of the theory relate to each other becomes crucial when a model is created to mimic the reality as good as possible. Simplifications are necessary but it has to be known that it will make the model less precise. If a model is on a computer it should be possible to use it during simulation which is not possible with a theory.

2.3 Choosing method

When choosing a method one will often ends up in the dilemma of methodology[13]. To be able to choose methodology it is important to know the

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[9] Forskningsmetodik (1997)
[10] Forskningsmetodik (1997)
[11] Forskningsmetodik (1997)
[12] Vetenskaplig metod (1996)
[13] Forskningsmetodik (1997)

purpose of the work and if the focus should be validity or trustiness. In many cases a combination of these methods are the best solution and it can help to get a congregated picture of the problem. It is also possible to begin with a mixed approach to investigate which of them that are most valid for a specified problem but it is not without difficulty. If the results are contradicting, which can be the case with a mixed approach, confusion can be the case.

2.3.1 Authors choice

In this master thesis both quantitative and qualitative research methods will be used but not as a mixed approach. My work will go through two different stages with a preparing qualitative phase to bring light to the problem and try to understand it followed by a quantitative investigation to prove the theory from part one, evaluate which information the test can give us, and then measure the capability of the method.

2.4 Information evaluation

Achieved results always have to be revised with criticism. Is the information we extract from measured data valid and do we measure the things we want? In this case, when developing a theory describing the procedure, the question will be if the theoretically defined variables and the measured ones correspond? The reliability of the information often depends on the accuracy of the test and measurements, how good instructions we have given to the respondents etc. In the second phase, where no respondents are involved, it is mostly the accuracy of the test and its setup that can interfere with the reliability.

In the end there is often a conflict between reliability and validity. The more reliable you want your results the more you will try to control the tests which will change them from being quantitative to become qualitative with a lower validity as a result. When a lot of measurements are done the variation between samples and within the measurement system can have a huge impact on the result. One way to monitor this is by always calculating the standard deviation when average values are used. If the standard deviation is too large one can not tell if the average value represents the test group.

2.5 Working process

To be able to know what is important and not, investigations of the procedure and the lapse will be carried out. To say which parts of the resulting energy curve that corresponds to what phenomenon is the goal. It is achieved by filming the procedure and develops a theoretical understanding and theory of what is happening during tearing. The theory should be able to cope with different material specifications and explain the change of the results.

When this deeper understanding is achieved and the critical parts of the energy curve are known measurements should be carried out using material with known characteristics. The different material characteristics that need to be detected by this mechanical tearing are:

- **Perforation strength**
  When the paperboard is perforated its remaining strength depends on the relationship between bridge and cut length on the knife, how deep you engage the tool through the board, and properties of the board.

- **Adhesion**
  The adhesion is a value of the force that holds two different layers of material together. In this case it is the adhesion between the aluminum foil and the inside polymer layer that is important and measured.

- **PE-strength**
  The strength of the inside polymer is due to both its thickness which is measured in g/m^2 and the composition of the polymer mix which decides its Young's modulus and elongation to break.

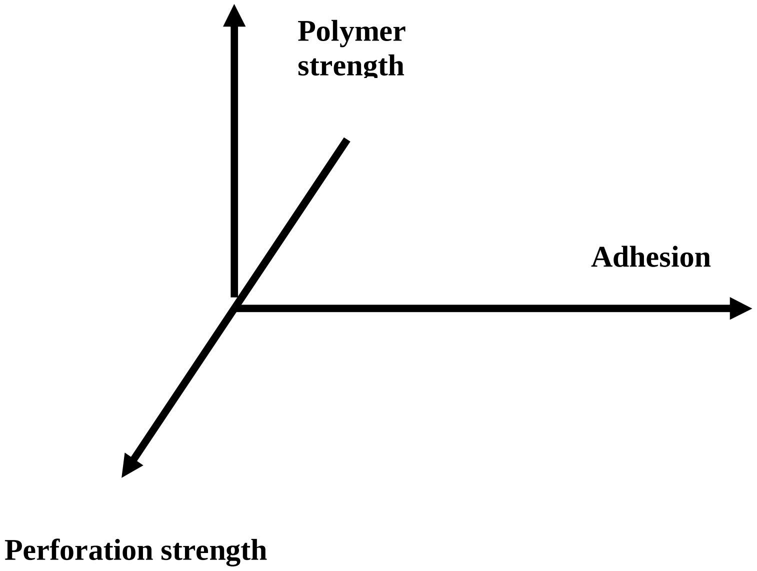

Figure 4 - Relationship discovered in earlier investigations[14]

A factorial experiment will be carried out to see which factor above that have a significant influence on the measured values.

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[14] TEA Perforation -Tetra Pak Development report

If differences in these characteristics can be seen the final part will be a Repeatability- and Reproducibility study to see how much the procedure needs to bee improved to be able to use the results with confidence.

2.5.1 Factorial experiments

Factorial designs are the foundation in most experimental designs for screening, optimization and robustness testing. They can be used either as full factorial experiments or reduced to fractional factorial experiments. Fractional experiments is a tool to reduce the number of experiments when the number of factors to test increase together with the possible number of variants.
Full factorial experiments are commonly used when two to four factors are tested but with more factors the number of tests and calculations gets to demanding and either screening or fractional tests are a better tool[15].

The name factorial design is related to the number of experiment that has to be carried out within a test. It is decided by the number of factors and levels of each factor to test. Three factors with one high and one low level of each factor result in $2^3 = 8$ rows in the test matrix and the same number of tests. See Table 1.

When analyzing the result one wants to see which factors or factor relationships that affect the measured response significantly. This is measured by calculating the effects from each factor and factor relationship to rank them. In a 2^3 factorial experiment there are three main effects and four interaction effects between two and three factors.

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[15] Design of Experiments, Principles and Applications (2008)

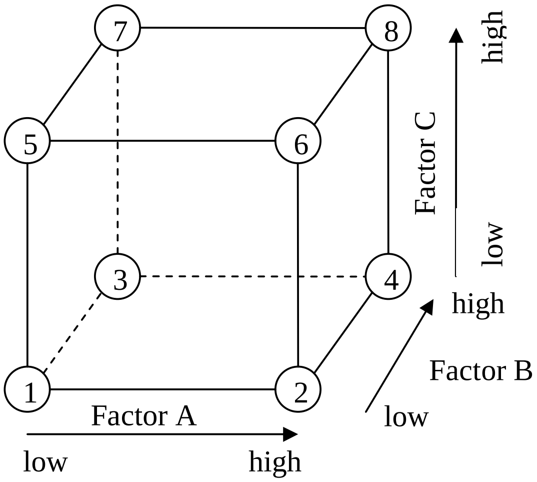

Figure 5 – 3-dimentional overview of a 2^3 factorial test

There are several ways to do a factorial test and analyze the data with computational software but there is also an easier by-hand method to compute the effects. This can be used when few factors and levels are tested and the result contains which factors and factor relationships that affect the response. When doing the "by hand" calculations the test matrix is vital and for a 2^3 test it looks like Table 1:

Table 1 - Factorial experiment test matrix

Test	A	B	C	AB	AC	BC	ABC	Response
1	-1	-1	-1	1	1	1	-1	R1
2	1	-1	-1	-1	-1	1	1	R2
3	-1	1	-1	-1	1	-1	1	R3
4	-1	-1	1	1	-1	-1	1	R4
5	1	1	-1	1	-1	-1	-1	R5
6	1	-1	1	-1	1	-1	-1	R6
7	-1	1	1	-1	-1	1	-1	R7
8	1	1	1	1	1	1	1	R8

(-1) represent the factor at its low level and (1) indicates the factor at high level. A, B & C are the main factors and the other four are interaction factors. The effect for each factor or factor relationship:

$$EffectA = \frac{\sum \overline{A}_{high} - \sum \overline{A}_{low}}{n}$$

where n is the number of samples tested.

There are different ways to present the effects from each factor and how it affects the response. Both normal plots and pareto diagrams can be used[16].
When several samples are tested for each combination it is also important to measure the variation within the samples to be able to say if the effect is significant compare to this variation. This can be done by using the limits of $\pm 3\sigma_{eff}$ which is common within most industries[17].

$$\sigma_{eff} = \sqrt{\frac{4}{N}\sigma^2} = \frac{2}{\sqrt{N}}\sigma_{estimate}$$ where N is the total number of samples.

$$\sigma_{estimate} = \sqrt{VAR}$$ where VAR is the variance for all tests.

2.5.2 Repeatability and Reproducibility

The Six sigma philosophy is something growing within Tetra Pak and the company is on the way to educate several employees to become Six Sigma black belt coaches. All companies contain processes for production, testing or administration etc. and Six Sigma is a tool to decrease the internal variation within these processes. The outcome should be a more reliable process giving a better and more precise result. Continuous improvements is the main goal and one of the competencies required by a black belt instructor is an improvement tool aiming to measure the variation within a measuring or testing system. The repeatability and reproducibility of the process is measured and the test is from now on called R & R[18].

A R & R measurement is a way to give every process a quantified number of its internal variation[19].

Repeatability: measures the variation of the measuring gauge by analyzing the result of one operator measuring the same sample several times.

Reproducibility: measures the additional variation when the same sample is measured with the same gauge by different operators.

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[16] Design of Experiments for engineers and scientists.(2003)
[17] Kompendie, Kvalitets och underhållsstyrning (2007)
[18] Six Sigma, continual improvements for businesses (2003)
[19] Concepts for R&R studies (1991)

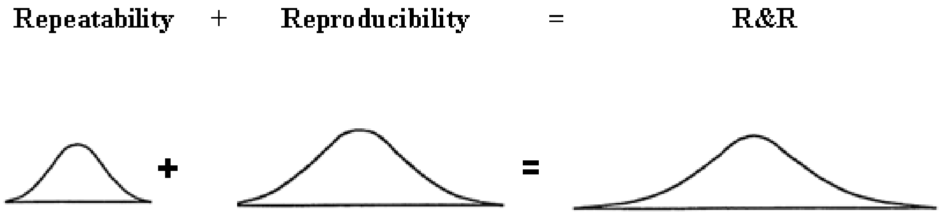

Figure 6 - Variations within R&R

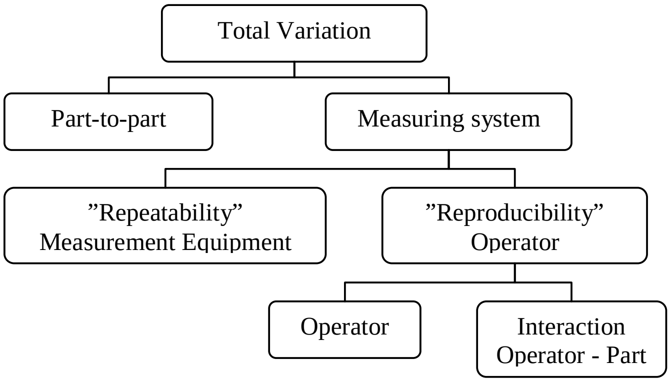

Figure 7 - Variations measured by the R&R

The R&R index, which is a percentage value, should for a measurement system be less than 30% to be acceptable, and below 10% to be world class. It can be calculated in many ways but it’s always a quota between the measuring system’s variation and the total variation of the test.

One needs to know that the R&R does not address the total measurement system and very important factors as calibration, stability and linearity are excluded due to that their impact is seen as less significant. Anyhow these factors need to be addressed and evaluated together with the R&R study.

Because of that the method is defined to measure the same sample several times sample variations will affect the result. When the test is destructive and the same sample can not be reused variations between samples have even bigger impact and can be a source for a bad R&R result. Sample variation is not addressed by the method but needs to be considered.

One of the most important issues that need to be handled to be able to classify a testing procedure is measurement discrimination. Do the equipment or method separate good and bad samples or material. This is often done by control- and specification limits and measurements of approved material should be within these limits.

2.5.3 Multivariate analysis, SIMCA

When studying, analyzing or trying to control a process there will always be measurements done and data collected. 50 years back in time measurement devices where expensive and the collected data was limited to a couple of infrequent measurements of few variables. Today’s reality is much different and both production and process industries aim for continuous monitoring and in line measurements ending up with huge amounts of data. To make sure that the most valuable information is extracted older data treatment processes has been abandon and newer multivariate tools have been developed. SIMCA is one of these tools developed by Umetrics and used within Tetra Pak.

SIMCA can treat and analyze huge amounts of data from many variables showing the result graphically which is easy to understand. One can analyze the data with either a PCA (Principal Component Analysis) or a PLS (Partial Least Square) approach. To find information among masses of process data one is projecting it down to few scores or principal components describing as much as possible of the process.

PLS, which is used in this investigation, is an extension of multiple linear regression. As linear regression handles one response at a time the results can be hard to interpret and PLS has more flexibility and address all resulting Y-variables at the same time. PLS modeling is also explicitly developed to handle situations with many correlating process variables as inputs.

Process data is divided in to five categories[20]:

1. **Controlled process variables:** Can be changed to affect the result
2. **Result variables:** Responses measuring the outcome of the process
3. **Characteristics of row material:** Input values, difficult to control
4. **Intermediate result variables:** Measured results within the process
5. **Uncontrolled variables:** Hard to influence, (eg air humidity, air temp).

Data is imported into SIMCA and named as either X,Y, qualitative X variables etc. The data is then used to build a model that is as similar to reality as possible. How good the achieved model is, is described by R^2 and Q^2 factors. “Goodness of fit” (R^2) shows how well the model and reality match and “goodness of prediction” (Q^2) is a value of the models ability to predict responses by looking at the inputs.

Numerous plots are made by SIMCA after the data is imported. In the summary plots one can get a model overview and see values as R^2 and Q^2.

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[20] SIMCA-P 12 User guide

To review the fit and investigate the model there are 5 basic plots to look at.
Scores: Displays trend, groupings and outliers.
Loadings: Displays the important variables and variable correlations. How important the X-variables are to describe Y
Coefficient plots: Displays the coefficient of the PLS model of each response.
VIP (Variable Importance Plot): Displays the overall importance of each X-variable to describe and correlate all Y responses.
Observed vs. Predicted: Displays the actual value versus the one predicted by the PLS model.

3 Theory

This chapter explains some theory regarding carton material and packages as well as the theory around perforations as openings and how they are produced in the converting process.

3.1 Paperboard technology

Trees in the forest consist mostly of wood fibers. To create pulp, which is used to produce paper and paper board, as much as possible of these fibers needs to be extracted from the wood. When pulp becomes paper the fibers bonds together in a structural network. To be able to understand the properties of Tetra Pak's carton board, which holds approximately 90% of the strength and stiffness in their packaging material, a study of paper and its nature have been done.

3.1.1 Fiber network

The structure of paper can be seen as a 2-dimensional network structure of fibers formed when the paper mass is dried and the fibers are connected to each other. The strength and formation of these fibers can be influenced by the production process and by that affect the final paper or board properties. Pine wood, which has a relative easy structure, has mostly 3-4 mm long fibers with a width of 50µm[21]. The alignment of these fibers in the network are affected by the production process and more fibers follow the machine direction than the cross direction which creates its directionality. Locally the properties of paper can vary due to formation and flocking. The fibers have a tendency to flock or connect to each other in groups which will change the fiber intensity across the material as well as the material properties in these spots[22].

3.1.2 Fibers

Regarding mechanical properties of paper it is not equivalent to treat it as a collection of fibers connected to each other. It has to be seen as a structure and this structure is often weaker than the fibers it contains. Investigations have also shown that a fiber dried within the network structure has lower strength than a pulled out fiber dried by its own[23].

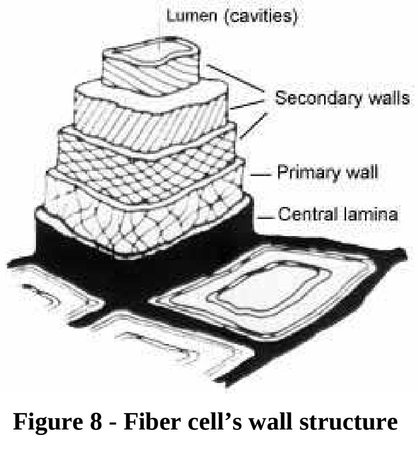

Figure 8 - Fiber cell's wall structure

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[21] Discussion with Johan Tryding, Tetra Pak Base Material
[22] Paper physics (1998)
[23] Paper physics (1998)

The wood fiber cell wall structure consists of several layers. The processing of the fibers decides how much of the fiber structure that you are able to keep intact and it affects the paper properties. As seen in Figure 8 the middle secondary wall is the thickest one and contributes the most to the fiber strength. Length is also a very important characteristic that influence the mechanical properties. The longer fibers there are within the network the more bonds can be established to other fibers with a stronger network as a result.
Studies of single fiber properties show a wide distribution of results, e.g. tensile strength values. That the variability arises from the biological raw material is probably true and the non uniform papermaking-process does not make it better[24].

3.1.3 Bonds

The paper strength comes from the bonding within the network and there are four types of bonds acting to hold the fibers together[25]

- Chemical bonds within cellulose molecules
- Intermolecular van der Waals bonds
- Entanglements of polymeric chains
- Inter-fiber bonds

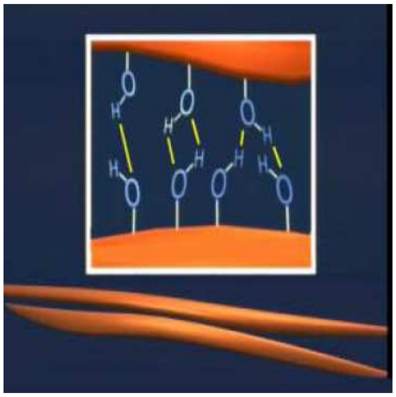

Figure 9 - Hydrogen bonds between fibers

The primary bonds between paper fibers are the chemical hydrogen bonds as well as van der Waals bonds which also are the only two that you can quantify with bonding energy. Hydrogen bonds which are much stronger are formed when a hydrogen atom bonds with a negative hydroxyl group between the fibers, [26] see Figure 9. The number of bonds that can be formed are limited and the better aligned the fibers are the more bonds can be formed. The directionality of the hydrogen atom to hydroxyl group bonds together with the rigid cellulose molecules make it difficult for these bonds to form in too dry paper.

When the paper is dry and contains less water the fibers come closer to each other and inter-fiber bonds are formed. In wet paper the water affect the possibility for hydrogen bonds and it is the weaker van der Waals bonds that

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[24] Paper physics (1998)
[25] Paper Physics (1998)
[26] Paper physics (1998)

hold the paper together. To further increase the wet paper properties fillers including polymeric mediators can be used to create covalent bonds that are strong and not affected by moisture.

3.1.4 Specific Tetra Pak board

Above the basics of paper have been studied and its fundamentals are also valid for board materials even if they are thicker and contains several layers. The board used in this investigation is a relatively thin with 80mN stiffness. It is a duplex board containing different layers giving it stiffness. An outer bleached layer covered with 2 thin layers of clay coat gives this material excellent printing property. By having duplex material built up by several layers the stiffness can be increased without having higher density or thicker material. The I-beam structure works like a composite and assures enough stiffness[27] of thin paperboards.

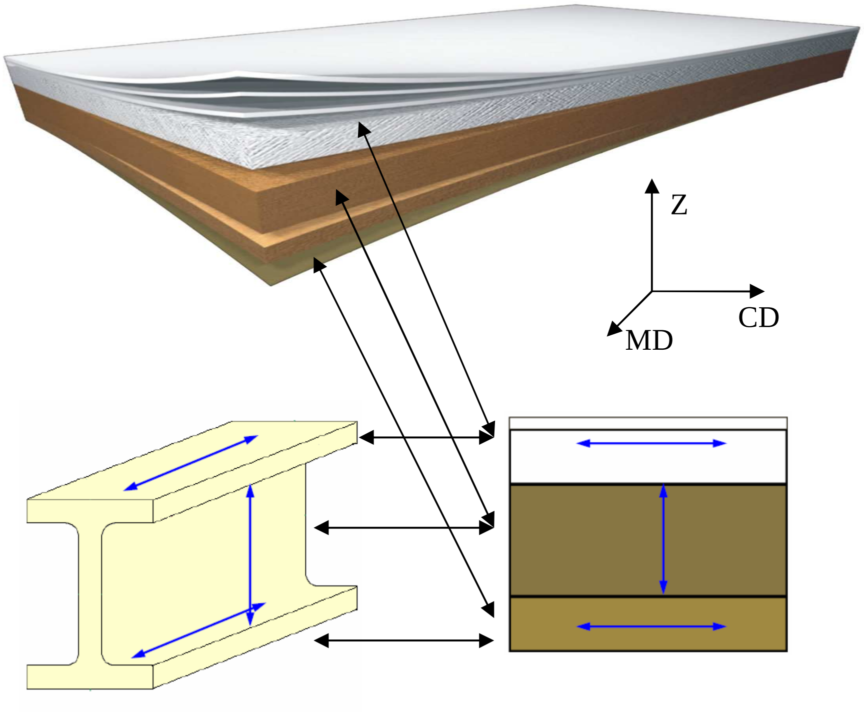

Figure 10 - I-bean composite structure in board[28]

In terms of tensile and tearing strength the I-beam structure is not increasing performance and could instead result in problems regarding the strength between the layers in thickness direction. This structure is also one of the

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[27] Paperboard Technology course, Tetra Pak
[28] Paperboard Technology course, Tetra Pak

reasons, together with the fiber alignment, that creates the strength and stiffness difference between machine-and cross direction.

Moisture does affect the properties of the board very much. Bonds are affected and the properties of the paper are changed due to moisture variations. It is a balance between board cracks with good fiber cutting properties, or having difficulties to penetrate the board with the knife[29]. In Tetra Pak converting process the moisture content vary between 5-7%.

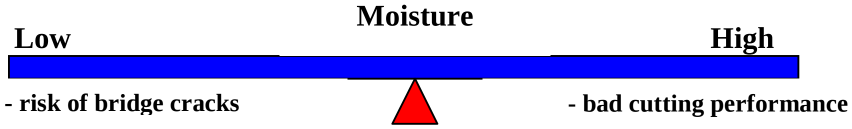

Figure 11 - Conflicting requirements

3.1.5 Paperboard properties

There is a couple of ways to describe paperboard materials and its characteristics. Paperboard gets its strength from the fibers and their bonding which makes the number of fibers crucial for any of the mechanical properties. By looking at a paper as a 2 dimensional structure the coverage and fiber intensity can be described as below.

Equation 1 – Coverage (2- dimentional system)[30]

$$c = N l_f w_f / A = b / \beta_f$$

Equation 2 - Reltive bonded area (2 dimentional system)[31]

$$RBA = \left[2cA - 2A(1 - \exp(-c))\right] / 2cA = 1 - (1 - \exp(-c)) / c$$

N = number of fibers
l_f = length of fibers
w_f = width of fibers
A= area
b = basic weight of paper
β_f = basic weight of fibers

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[29] Paperboard Technology course, Tetra Pak
[30] Paper physics (1998)
[31] Paper physics (1998)

- Tensile strength (N/m): T = F/b

- Stiffness (mN): The stiffness is described by the maximum force needed to bend a 38mm wide strip 15°.

- Z-tensile strength (kPa): The pressure needed to pull a sample apart in Z-direction separating 2 of the several board layers.

- Roughness, Bendtsen (ml/min): Measuring of the airflow between a circular measuring head and a flat paperboard sample. The air is able to flow due to the uneven surface of the board.

3.1.6 Board breakage

There are two different ways to break paper board and its network structure of fibers. Depending on the bonds between fibers within the network structure a fiber is either pulled out or broken when put under tensile load. During fiber pull out breakage, the energy is decided by the length of the fibers and the number of linking points. The external load, applied on the network, will pass from fiber to fiber through shear forces until the bonds can not hold any longer[32] and the fiber is pulled out. See Figure 12

The number of linking points, and by that the breaking energy, can be increased during processing of the paper. Calendaring, which compress the board and increase the basic weight of the material results in closer fibers and more connections and fiber to fiber friction? Tearing energy is increased by calendaring to a point when the bonding energy is as high as the tensile strength of the individual fibers which will cause them to break instead of being pulled out.

According to Figure 13 one can see how tensile strength is increased by higher RBA achieved by calendaring. One can also see that increased fiber length, width, and bond strength are a much more effective to increase tensile strength but harder to achieve.

Equation 3 - No fiber failure, weak bonds[33]

$$T = N_y \cdot RBA \cdot \tau_b \cdot w_f \cdot \frac{l_f}{2}$$

Equation 4 - Some fiber failure

$$T = N_y \cdot F_f \left(1 - \frac{F_f}{2 \cdot RBA \cdot \tau_b w_f \cdot l_f} \right)$$

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[32] Paper physics (1998)

[33] Paper physics (1998)

T = Tensile strength
N_y = the number of fibers that cross a unit fracture line
τ_b = breaking stress of bonds
F_f = Fiber strength

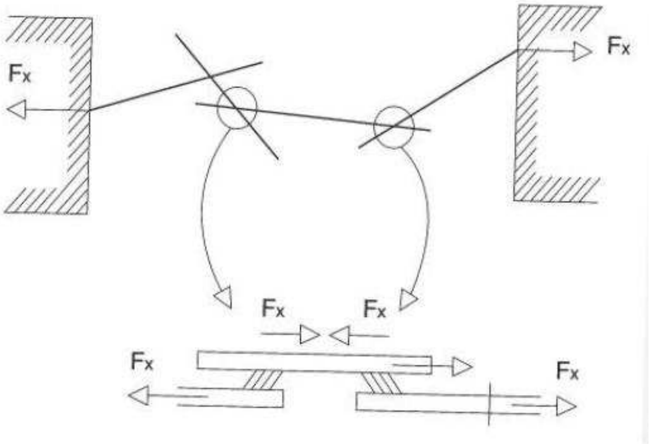

Figure 12 - Shear forces between fibers[34]

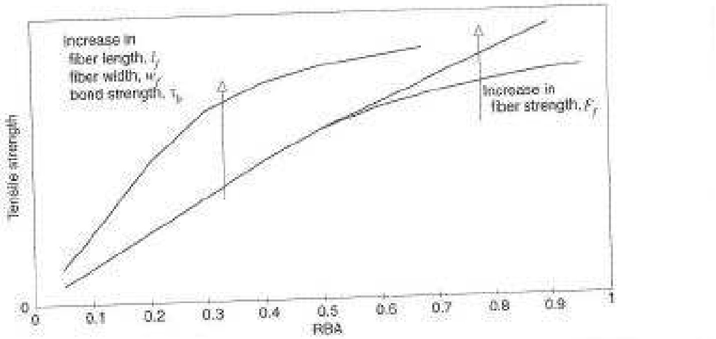

Figure 13 - Improving tensile strength by increased RBA[35]

In the literature there are many different models regarding tensile strength of paper. It is not known which of them that is right or wrong but one should know that the variations of the models are far less than the uncertainty in deciding the microscopic parameters they use. Parameters as bond- and fiber strength, coverage, RBA etc. are not trivial to measure or estimate and the achieved results by using these parameters are as uncertain[36].

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[34] Paper physics (1998)
[35] Paper physics (1998)
[36] Paper physics (1998)

3.2 Converting process

During the converting process, material aimed for Tetra Brik Aseptic packages goes through three main stages as seen in Figure 14.

Figure 14 - Converting process

1.5 meters wide paper board rolls are delivered from the supplier and arrive at the printing press. This is where printing, creasing, and cutting are done and out comes material with the final print, creases to be able to fold the packages as well as perforations and contingent punched holes for straws or screw caps. After the printing station the material arrives to the laminator where it is laminated with aluminum foil, extruded polymer and in some cases plastic film. The material is now complete and the last step is slitting. At this stage the wide roll, in this case containing seven lanes of packages, is slitted apart to have the width of one package and to be ready for the filling machine. From now on a lane is called web which is the Tetra Pak expression.

3.2.1 Crease tool

The perforations are made in the printer where the carton runs through a creasing tool consisting of rolling cylinders equipped with anvils and knives that cut all the perforations. This is a high speed procedure and the carton runs in several hundreds m/min through this tool. One big challenge is to assure that all the hundreds perforations that are made every second along the width of the wide roll have the same quality and follow the specification. The engagement of knives is set very precisely and changes in centesimal of a millimeter can affect the opening or integrity performance.

3.3 Perforation Design

The aseptic technology is protecting the content and perforation is one of many solutions to be able to open the package in a convenient way. The perforation is not more than a line where a knife and its teeth have cut into the paper board to make it weaker. Along this line, consisting of cuts and carton bridges, consumers are able to tear an opening in the packaging material which can be used to pour the content of the package. The perforation comes in many different shapes depending on the package size and shape. The relation between tooth and gap on the knife vary both between different shapes, different board types, as well as between different sections of the perforation knife. The designs are chosen to be able to tear it as easy as possible at the same time as integrity is not conceded and converting stays simple.

3.3.1 Integrity vs. openability

Figure 15 - Plastic residues

The main focus for Tetra Pak has always been and will continue to be integrity which means that leakage from inside or outside is unacceptable. With this focus, openability has been forgotten and lately problems to open perforated packages have been discovered. The more one perforates the material the weaker the package will become and leakage will be the effect. But on the other hand if the depth of the cuts are not deep enough and do not go through the printed board it will be very hard to tear and the problems with openability come up. Aluminum foil and increasing polymer weights are also affecting the openability and that is why this problem only occurs on aseptic packaging solutions. Lower adhesion between the inside polymer and the aluminum foil together with the higher strength of the polymer can cause plastic residues blocking the hole after tearing is done, see Figure 15. An infinite headspace is also conducing to this problem because of how different liquids affect the adhesion of the inside polymer during storage.

3.4 Aseptic technology

Aseptic technology achieve a totally sterile packaging system where no air or bacteria comes in to the packages and they can stay fresh for a much longer time, often even without being refrigerated. Some of the differences between an aseptic and a non aseptic package will now be mentioned.

3.4.1 Headspace

When filling packages the final liquid level in the closed packages can be chosen. The distance between the liquid level and the top of the package is called headspace. Within aseptic technology no air should be contained inside the package together with the content and one solution is to increase the filling level to 100%. In some cases this is not possible, e.g. if the content needs to be shaken before opening, and this issue can be solved by filling the headspace with an inert gas or sterile air.[37]

3.4.2 Material

If the content of an aseptic package should be able to stay fresh for a longer time it needs a higher protection from the outside. This is achieved by the

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[37] Head pace, Tetra Pak internal webpage (2008-09-26)

different material structure used in aseptic packages. Aluminum foil is added to work as a light and oxygen barrier[38]. The packaging material aimed for aseptic products also needs more polymers to assure the integrity for a longer time. An adhesive polymer also help the aluminum to stick to the paperboard as well as increase the adhesion between the inside layer polymer and the aluminum foil. In figure 5 one can see the material structure and how the different layers act to keep the beverage separated from the outside environment.

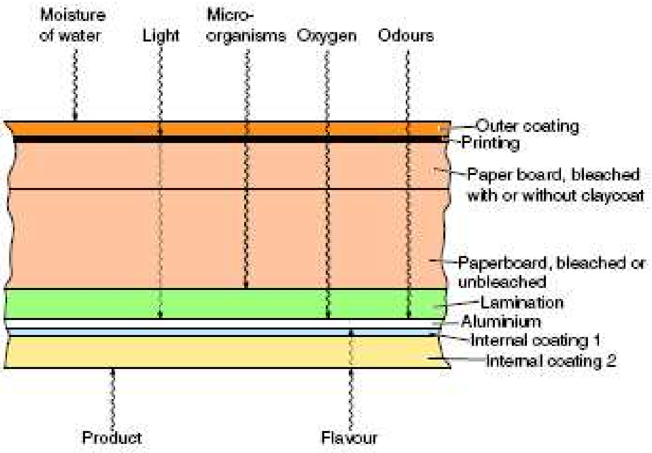

Figure 16 - Packaging material structure[39]

3.4.3 Sterilization

Aseptic packages are filled in a sterilized environment and together with sterilized material and beverage the final packages are sterile and bacteria free. The liquid is UHT (Ultra High Temperature) treated prior to the filling machine and the material runs through a hydrogen peroxide bath at 70°C or is sprayed with hydrogen peroxide getting the same effect. The UHT treatment process implicates a short increase of temperature to elicitate existing bacteria and microorganisms without giving the beverage the taste of being preheated[40].

3.5 Fracture Mechanics

To be able to understand the breakage of the board the basics of fracture mechanics have been studied which are the foundation of how material can resist breakage and failure.

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[38] Packaging Material basic knowledge
[39] Packaging Material basic knowledge
[40] UHT, www.tetrapak.com 2008-10-20

3.5.1 Modes of fracture

In fracture mechanics there are three different fracture modus defined depending on the applied load.

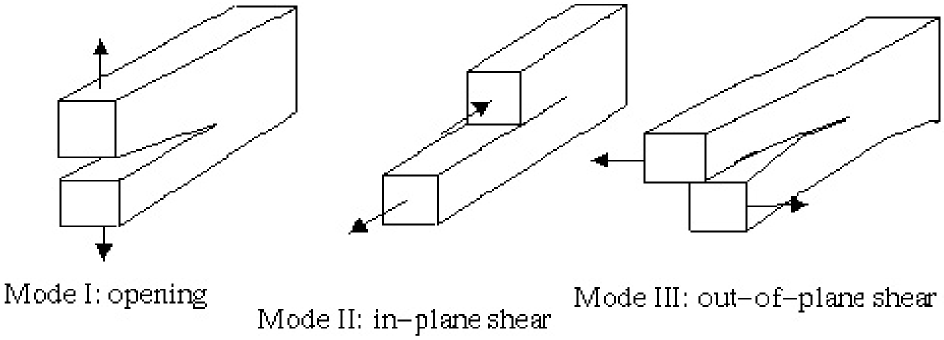

Figure 17 - Fracture Mechanics modus

The stress intention factor in the crack tip, which is what forces a crack apart and let it propagate, is different for these three modes[41].

$$K_I = \lim_{x \to +o} \sigma_y(x,0)\sqrt{2\pi x}$$

$$K_{II} = \lim_{x \to +o} \tau_{xy}(x,0)\sqrt{2\pi x}$$

$$K_{III} = \lim_{x \to +o} \tau_{yz}(x,0)\sqrt{2\pi x}$$

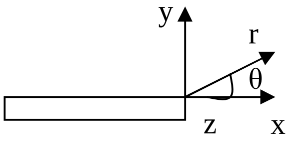

Figure 18 - Coordinate system

The three intensity factors depend on crack dimensions and loading conditions and to make a crack propagate the intensity factor needs to exceed the fracture toughness K_C which is seen as a material parameter. In general cases there is often a mix mode containing all the three modes described in Figure 17 and superposition is used to regard all three modes at once[42].

3.5.2 Material weakening by perforation

The perforation is done to weaken the package material along a line and by that enable the package to be torn opened by hand instead of using a pair of scissor. The cuts in the perforation should always go the whole way through the board and it is the bridge length, separating the cuts, which should control the remaining strength of the board. By doing RTS (Relative Tensile Strength)

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[41] Formelsamling Hållfastighetslära

[42] Advanced Mechanics of Materials (2003)

measurements, for example on perforated printed board, one can see that the relative value of force needed to pull a 15mm wide sample apart with and without perforation is similar to the pitch in percent as long as the cuts goes fully through the board. With this in mind and looking at the remaining strength of the board one says that the fibers in the bridges are unaffected by the perforation knife and the fibers in the cut are broken.

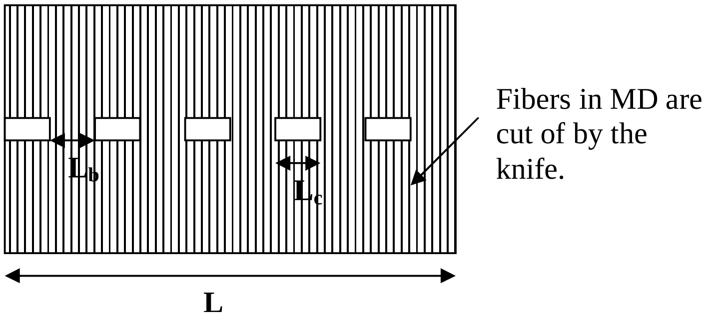

Figure 19 -Schematic picture of perforation and fibers

Example according to Figure 19:
Length of sample (L): 7,5mm
Length of bridge (L_b): 0,9mm
Length of cut (L_c): 0,6mm
Tooth Pitch (P): $\frac{L_b}{L_c + L_b} \cdot 100 = \frac{0{,}9}{0{,}9 + 0{,}6} \cdot 100 = 60\%$
Tensile strength material (T):17 kN/m

Remaining strength after perforation
(T_p): $T_p = L \cdot P \cdot T = 0{,}0075 \cdot 0{,}6 \cdot 17 \cdot 10^3 = 76{,}5N$

When tearing a package the possibility to tear along the perforation is a very important factor. When the tearing loose track of the perforated line it is not controllable any longer and bad opening can come as a result. To enable good tearing that follows the perforated line there are more factors than the remaining strength that contribute to good performance. The remaining strength of the material is decided by the tooth pitch but the relationships of bridge and cut is not irrelevant. If each cut in the perforation is seen as an internal crack the energy concentration at the crack tip can be something to consider when designing perforations. If the rectangular cut is simplified with an elliptic shape the energy concentration at the crack tip is influenced by the length/width relation of the crack[43].

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[43] Advanced Mechanics of Materials (2003)

$$\sigma_{\max} = \sigma(1 + 2\frac{a}{b})$$

$$\sigma_{\min} = -\sigma$$

Example:

For a/b = 1 (circular hole)
$\sigma_{\max} = 3\sigma$

For a/b = 5
$\sigma_{\max} = 11\sigma$

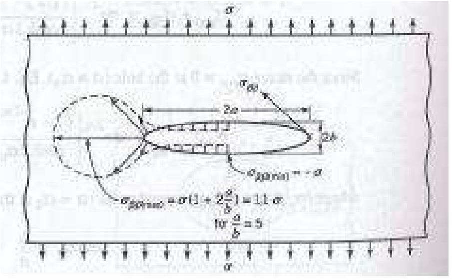

Figure 20 - Energy concentration at crack tip

One can see that the longer/thinner cuts the perforation consist of the higher factor a/b will become as well as the energy concentration at the crack tip. The higher this concentration is the more of the applied energy during tearing will try to break the bridge between two cuts.

4 Mechanical tearing method and material

This chapter describes the mechanical tearing procedure and the material used for this investigation.

4.1 The equipment

Mechanical tearing is used to be able to exclude most of the human variations during tearing of perforations. It also makes it possible to do quantitative measurements and compare the results and how tearing is affected by different material recipes, process specifications and perforation qualities.

4.1.1 Machine

The machine used is a tensile tester, Zwick/Roell Pro-line, with a vertical force measurement system. The load-cell is valid up to 1 kN vertical force. The tearing proceeds with constant speed and the vertical force is measured during the whole lapse. In Figure 22 one can see the clamps and how they are mounted before measuring.

Figure 21 - Instron measurement system

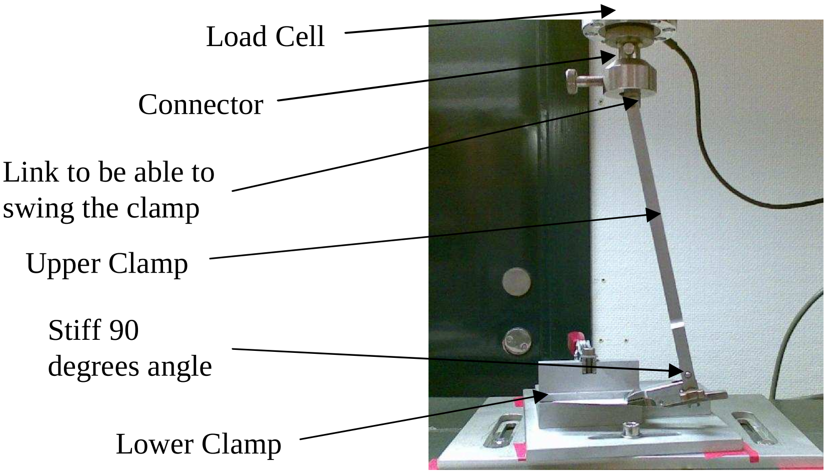

Figure 22 - Mounted clamps ready for measuring

4.1.2 Clamps

The clamps are designed to as good as possible mimic the natural tearing procedure done by human hands but with necessary differences. The bottom clamp holds the specimen along the perforation and is also a support during tearing. It is fastened in the bottom plate of the machine with screws and it is shaped to allow maximum support during tearing without interfering with the moving upper clamp.

The upper clamp, which clamps on the other side of the perforated line, is attached on a long arm. As little material as possible is put in the upper clamp's gap to assure that as few bridges as possible has to be torn simultaneously when tearing begins.

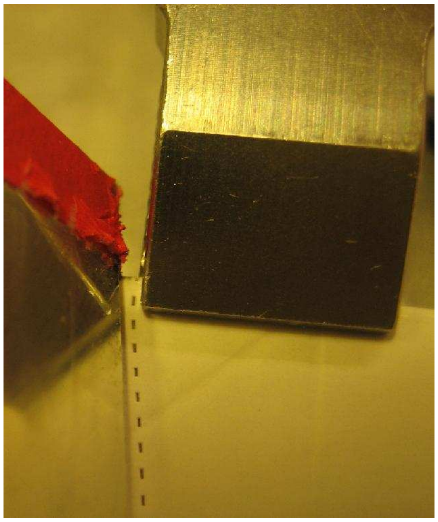

Figure 23 - How clamps are attached on both sides of the perforation.

4.1.3 Test program

TestXpert II is the software, provided by Zwick, which controls the measurements and one can decide what to measure and how to present the results. In this case the raw data, which comes as .TRA files, are used to evaluate and do calculations of the measurement in Excel.

4.1.4 Input values

Sample rate: 100 Hz
Test speed: 400 mm/min
Tearing distance: 25 mm vertically

4.2 Specimen preparation

Specimens are cut and folded from either printed board or laminated packaging material delivered in small rolls. They are cut into sheets of package size and then folded in the middle of the perforation to be able to tear them. After this it is cut on both sides to a smaller size that fits the machine. A template is used to assure that every sample is folded the same way and with as less variation as possible.

During the initial qualitative study sometimes only one side of the perforation of printed board material is used. This means that the sample is not folded and instead is cut in half at the middle of the perforation.

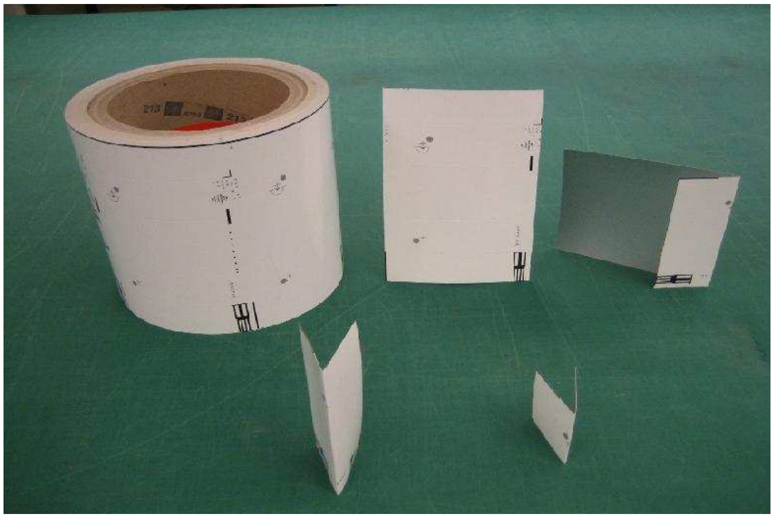

Figure 24 - From roll to final sample

4.3 Measuring procedure

During most of the measurements 10 samples of each material variant and knife setting are tested. The force is zeroed between every test before the new sample is mounted in the clamps in as similar way as the previous one. The test begins and after 25 mm vertical distance the result is presented and the upper clamp returns to its initial position.

4.4 The material

The material used during this master thesis is produced in Jurong, Singapore. The converting factory is equipped with a standard line VT-Flex printer and a laminator capable of high speed lamination.

4.4.1 Board

The board is supplied from two different suppliers which are among the most common board types used in TBA portion packs production. There are some differences in structure and performance of these boards e.g. tensile strength, roughness, grammage, fiber length etc. In this work they are named A and B.

4.4.2 Perforation

Each roll in the converting process has seven webs and the perforation knives are set individually. When producing this material one has used this possibility to create different perforation strength on all 7 webs. By this it is possible to compare how the knife type and its engagement affect the results and if material from a center web performs differently compare to one on the edge of the roll. Negative engagement means that the knife is set to push against the anvil and by that perforate through the board. A positive engagement creates a gap between the rolling knife and the anvil which result in that the cut is not done entirely through the board, called partial cut. Both light knives with a 60% tooth pitch and standard knives with a 50% tooth pitch are used. In *Appendix A* one can find microscope pictures that shows the difference between some engagements.

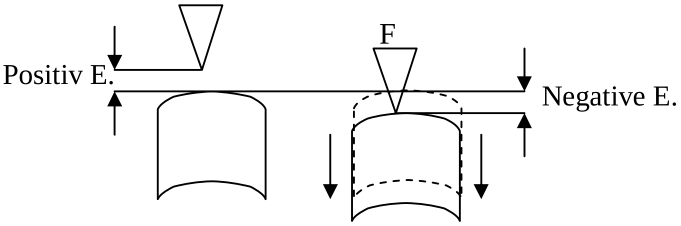

Figure 25 - Engagement setting of perf. knives

4.4.3 Polymer

The polymer on the material for this test consists of four layers. The two most inner layers are called the Inside 1 & 2. See Figure 16 on page 24.

To be able to create different types of polymer strength within this test two different grammages of the inside 2 polymer are used. One level is according to specification and a 15% increase of grammage result in a thicker and stronger inside layer used as a high level according to Table 2 on page 32.

4.4.4 Lamination

Lamination, which is the process where polymer and aluminum foil are laminated to the board, can be set up in many different ways. The complicated process contains a lot of possibilities and for this test one has tried to create different values of adhesion, which is the force holding the inside polymer layer together with the aluminum foil, by changing two of these parameters. In previous tests two process factors have been identified to change adhesion between these two layers. When producing material for this test these two factors are run on two different levels to try to create low and high adhesion. The factors are Die offset, controlling if the melted polymer touch the material or the chill roller first, and Line load pressure controlling the nip force between nip roller and chill roller at the *Inside* extruder station.

4.4.5 Number of variants

In total there are 35 different variants of laminated packaging material available for testing. In Table 2 one can see how the 5 variants and 7 different perforation engagements result in these 35 possibilities. Due to the time consuming tests the most important material combinations are chosen for each test to be able to do as good evaluations as possible.

Table 2- All avaible material variants

Variant		**1**	**2**	**3**	**4**	**5**
Adhesion **PE-strength** **Board**		High Low A	Low Low A	High High A	Low High A	Low High B
	Knife / E					
web 1:	Light 0.00					
web 2:	Light -0.02					
web 3:	Light -0.06					
web 4:	Light -0.00					
web 5:	Light +0.08					
web 6:	Stnd 0.00					
web 7:	Stnd -0.06					

5 Qualitative tests

This chapter describes the first qualitative tests done to get a greater understanding of both the mechanical tearing procedure and the results it gives.

5.1 Answers needed

In this first part of testing one needs to get a better understanding of the mechanical tearing process to be able to create a good foundation for further testing and data analysis of perforations torn by mechanical tearing according to *4 Mechanical tearing method and material*. At this stage of the study there is no decision of how to measure and analyze the results or how to compare different materials. There will also be tests to try to answer the question if we break the bridges in the perforation by tensile break or tearing when using the mechanical tearing method.

5.2 Planned tests

All qualitative tests will here be described one by one and the results will follow in chapter *5.3*.

5.2.1 High speed filming

The purpose is to film the mechanical tearing procedure with a high speed camera to get an assumption of what is happening during the tearing. With different angles and zooms one wants to achieve as good pictures as possible that can explain how the material cracks along the perforation. The material used is a laminated board with well penetrating perforation engagement and it is folded as explained in Figure 24 on page 30.

5.2.2 Starting with cut or bridge

The next test is to see how the tearing result, especially the energy peak, is affected by the fact that there can be either a cut or a bridge at the material edge. Samples used are only of one sided printed board material without folding to get results that are as easy to interpret as possible.

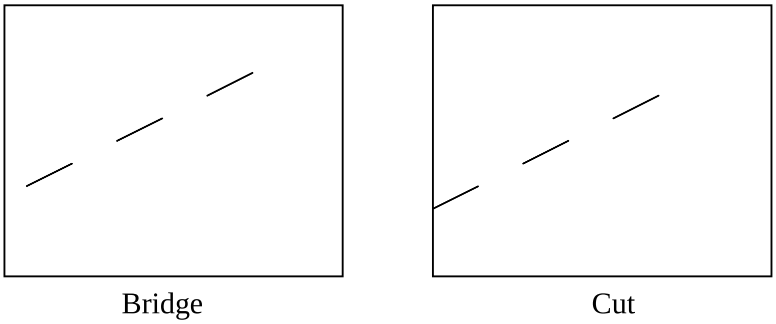

Figure 26 - Bridge & Cut samples

A 80 mN printed board of type B with ±0.00 engagement is used and 5 samples each with either a bridge or a cut in the beginning are tested. The material was produced in an earlier test loop in Jurong, Singapore during spring 2008.

5.2.3 Engagements

Test is done on one sided printed board material. It is done to both see the differences of result due to different perforation engagements and knife types as well as to get further knowledge of how to improve the analysis of the data. The 80 mN board from the latest Singapore production is used and 5 samples each from web 2-7 are tested.

5.2.4 Tear vs. Tensile breakage

An important question to answer is, “Is a perforation opened by mechanical tearing torn or pulled opened when looking at every individual bridge?” Are the bridges cracked by fracture mechanics Modus I or III?
Comparison is done by using both a tensile tester to pull a perforation sample (Modus I) as well as a tear test that should be as close as possible to complete tearing (Modus III).

The goal of this test is to estimate if mechanical tearing measures a Modus I or Modus III breakage of the perforation bridges. This is done by comparing the force needed in these two tests with the average force after the peak in mechanical tearing.

The tensile test is performed in an Instron machine similar to the Zwick described earlier. A 35 mm wide strip is cut out containing perforation in the middle. The force (F) needed to break the perforation bridges one by one during constant speed is measured. The goal is to break the bridges one by one with a constant average force and this is achieved by mounting the sample so that the tearing starts at one side and continues across the sample. By doing this one wants to obtain a Modus I crack opening.

Load cell: 10 kN
Speed: 20 mm/min

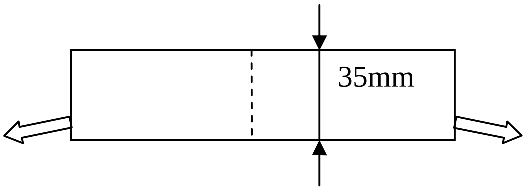

Figure 27 - Sample for tensile test.

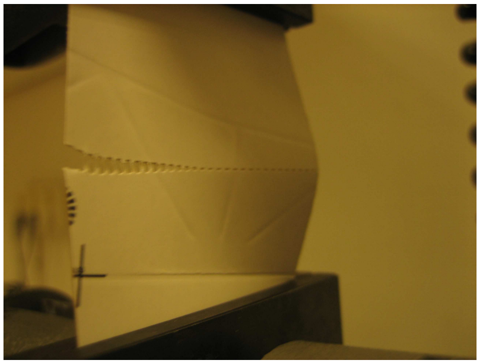

Figure 28 -Tensile breakage perforation

To achieve and measure Modus III tearing different methods have been tried out. A tear tester build on the Elmendorf's[44] principle was first tried but it did not tear along the perforation and because of that it is a dynamic method it would be hard to compare its result with the static tensile method.
The next method tried out is based on a measuring method used at a paperboard supplier Frövi in Örebro, Sweden[45].
The sample is cut as shown in Figure 29 and mounted in the machine as an upside down Y seen in Figure 30.

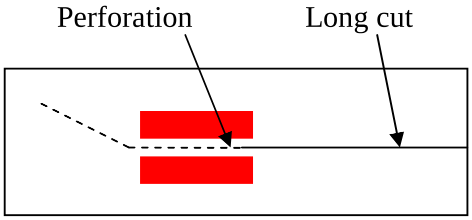

Figure 29 - Sample for tear test

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[44] http://www.astm.org/Standards/D689.htm, (2008-11-21)
[45] Y-peel characterization of adhesively-bonded carton board: an objective method.(2007)

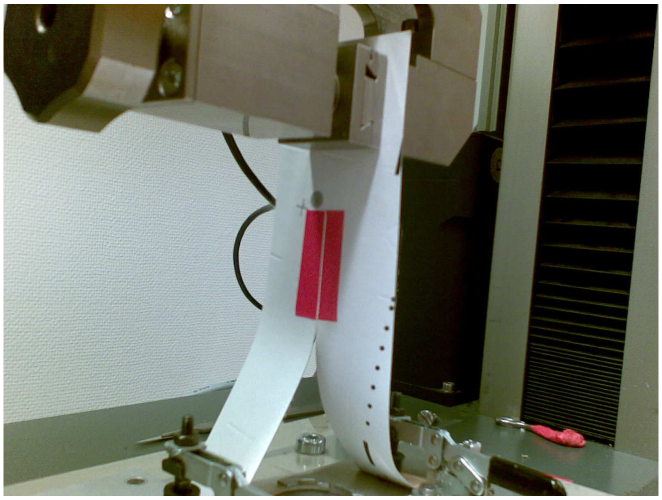


Figure 30 - Y tear test

A piece of tape as seen in Figure 30 is put on each side of the perforation to prevent delaminating of the board and keep the tearing to the perforated line.

Load cell: 1 kN
Speed: 20 mm/min

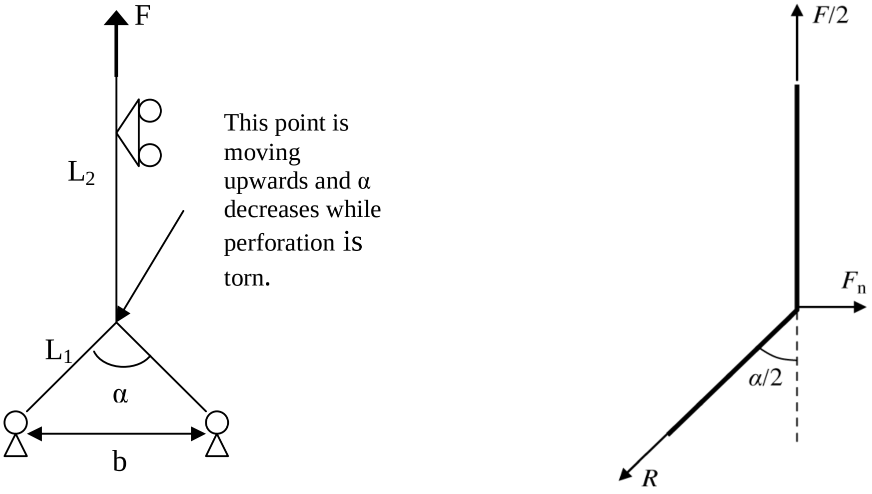


Figure 31 - Y-tearing principal and forces [45]

The force acting on the perforation and its bridges are denoted F_n. F is the force measured by the machine and the angle α is changing during the test.

$$\alpha = \sin\left(\frac{0{,}5 \cdot b}{L_1}\right) \tag{1}$$

$$\frac{F}{2} - R\cos\left(\frac{\alpha}{2}\right) = 0 \tag{2}$$

$$F_n - R\sin\left(\frac{\alpha}{2}\right) = 0 \tag{3}$$

Combining eq. 2 & 3

$$F_n = \frac{F}{2}\tan\left(\frac{\alpha}{2}\right)$$

In this test four different materials are tested with both B and A boards together with light and standard knives. The four variants are from web 3 and 7 which both have -0.06 as perforation engagement. 5 samples of each variant are tested and compared.

In both these tests an approximation is used. Even if the perforation bridges are torn one by one from one side to another it is more than one bridge at the time affected by the applied force. One can not think that the force distribution is the same in both cases seen in Figure 32 and when tensile force is used it is definitely a more linear distribution than in the Y-tear that probably has a more exponential force distribution.

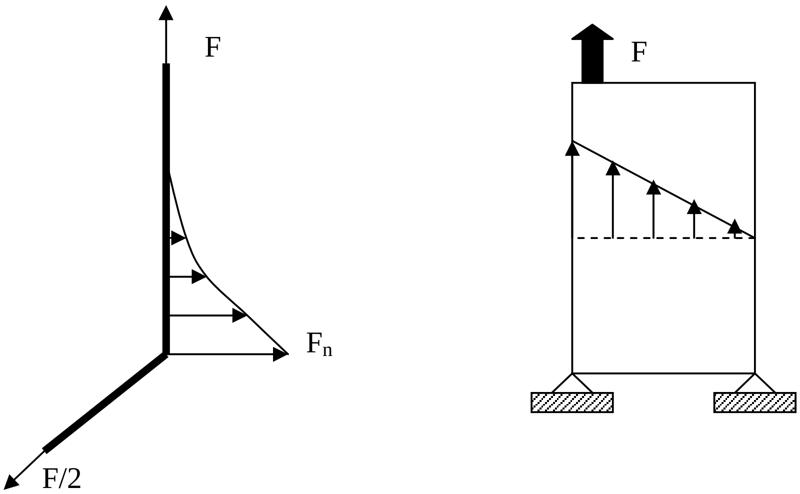


Figure 32 - Force distribution

5.2.5 Fiber pull out

The force needed to break the board is depending on the number of fibers that are pulled out or cracked according to chapter *3.1.6 Board breakage*. To see if there is a major difference in how the board and its fibers break a microscope investigation of cracked bridges is done on similar material from both the tensile and the tear tests.

5.2.6 Process description

To increase the knowledge about the process and what is measured during a lapse all parts and what force that affects them during tearing are investigated. The important parts that are investigated are everything in between the measuring load-cell and the breaking perforation bridge. This investigation is done looking at the process when it is standing still somewhere in the middle of the tearing. This instant can be seen as valid for the majority of the lapse after tearing is initiated. Many parameters are known and do not change but there are also some of them that are related to the stiffness of the board which can vary.

5.3 Results

In this part all the results from described tests will be presented one by one.

5.3.1 High speed filming

The high speed filming made it possible to watch the tearing both from a distance as well as close up views in slow motion. By comparing the films from different angles and the resulting energy curves it has been possible to link curve characteristics with the tearing operation. When the tearing followed the perforation a curve as below was achieved which can be seen as a perfect curve without disturbances.

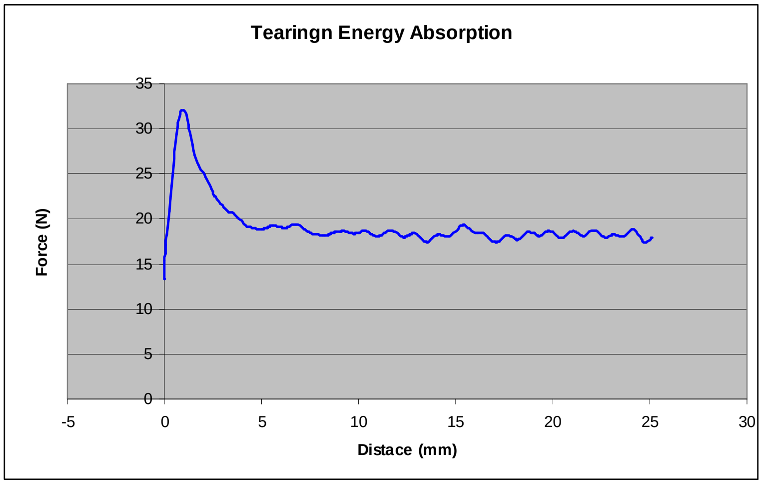


Figure 33 - Typical energy curve

The filming also made it possible to extract snapshot pictures from the high speed film. In Figure 34 one of these pictures is showing the side of the perforation facing down during tearing. The shining piece between the two breaking bridges is the polymer elongating before the breakage.

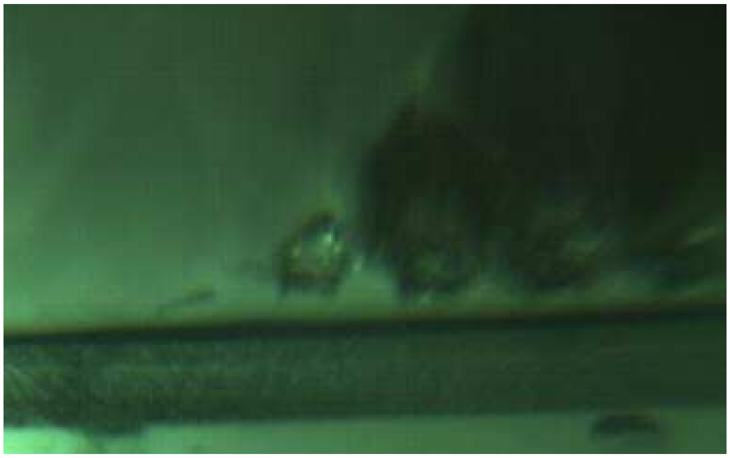


Figure 34 - Snapshot of breaking bridges and polymer

5.3.2 Starting with cut or bridge

The test result contains energy curves, bar chart showing total energy, average graphs comparing cut and bridge as well as a table with measured values for all samples. One can see that the sample called *Bridge 5* distinguishes from the others and by looking at the torn sample it is possible to see that the board have delaminate which affects the result and increase the tearing energy.

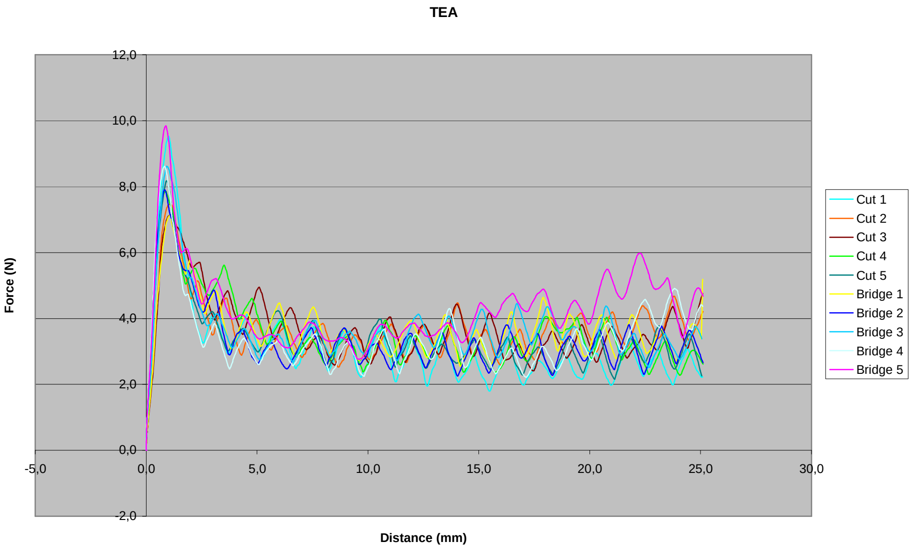


Figure 35 - Energy curves bridge vs. cut

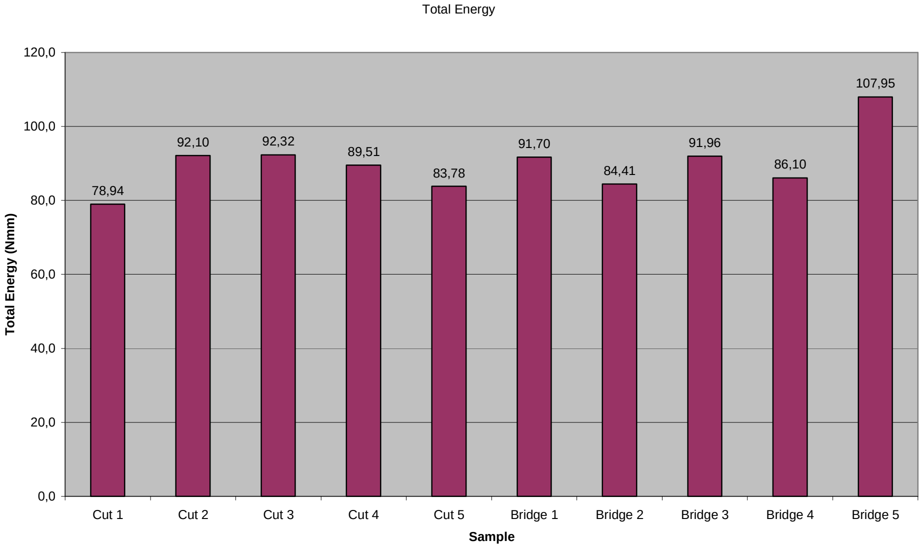


Figure 36 - Total energies bridge vs. cut

When looking at the total energy for the ten measurements it varies between 79 and 92 Nmm if the test “Bridge 5” is seen as an outlier.

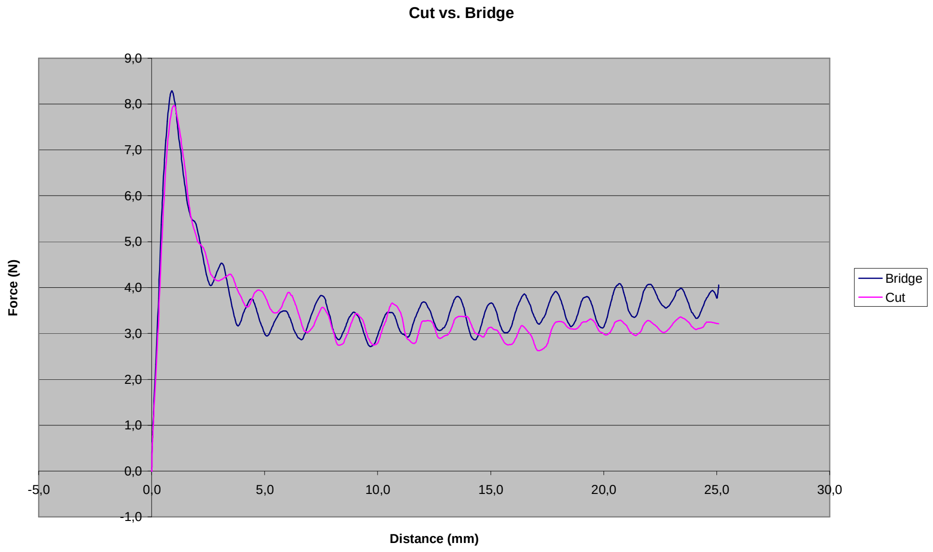


Figure 37 - Average curves Bridge and Cut samples

When two average curves are created, one for the bridge and one for cut samples, the difference is hard to notice. The Peak load is nearly the same, 5% difference, and there is only a small rise of force in the end of the Bridge curve that separates them.

5.3.3 Single side printed board

The result contains different energy curves and bar charts from measuring 6 different webs with different engagements and knife types. Figure 38 and Figure 39 show the average results from each web. Since some of the samples did delaminate and tear outside the perforation Figure 40 and Figure 41 show only one measurement from each web that did tear as it should, i.e. along the perforation.

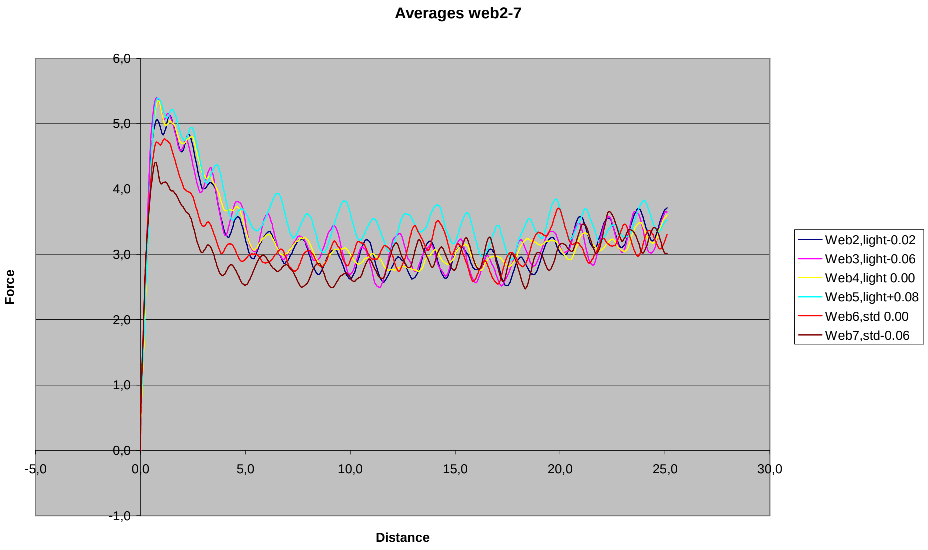


Figure 38 - Energy curves different engagements

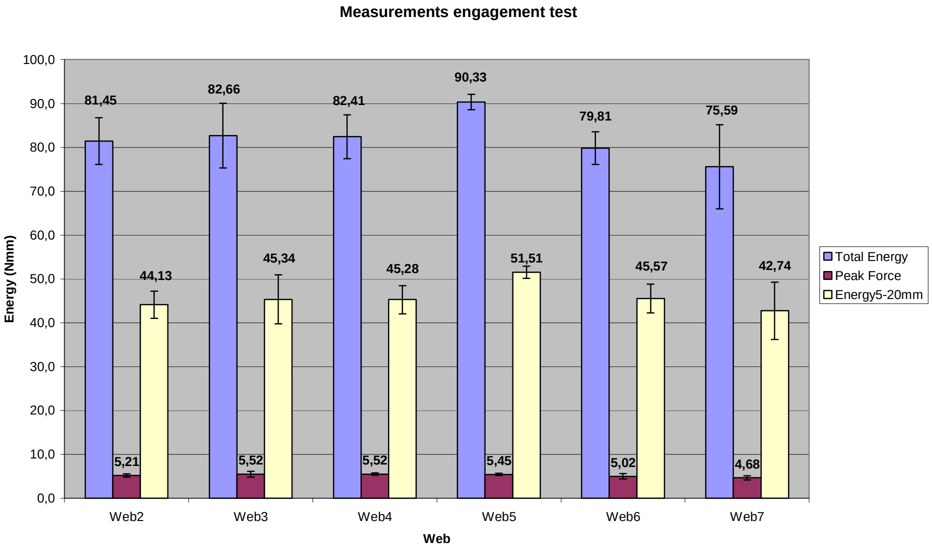


Figure 39 - Bar chart measured values

In Figure 39 one can see that the total energy does not change between web 2-4 but increases for material from web 5. When the standard knife is used on web 6 and 7 the lowest total energies are measured. The Peak load is not changing very much except for the standard knives on web 6 and 7 were it decreases a bit. The yellow bar shows a new measurement that quantifies the energy for only one part of the curve. To reduce the variation of the peak the energy between 5 and 20 mm of vertical tearing is chosen and the values have a similar relationship to each other as the Total energy.

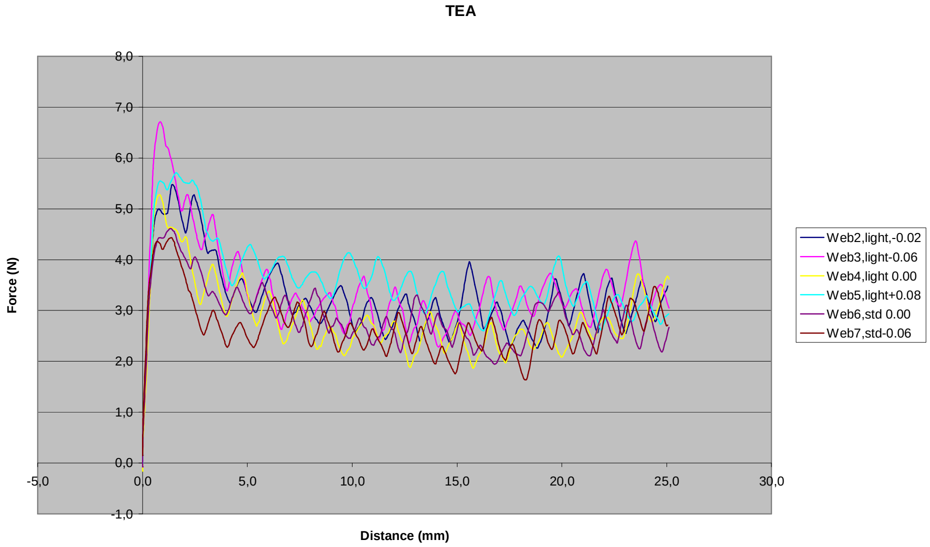


Figure 40 - "Good" samples

Studying the “good” samples in Figure 40 and Figure 41 show more difference than the average values in Figure 39. The “Energy 5-20 mm” follows the Total energy relationships and the Peak load scores highest at web 3, even if it has a deep engagement, and lowest among the standard knives used.

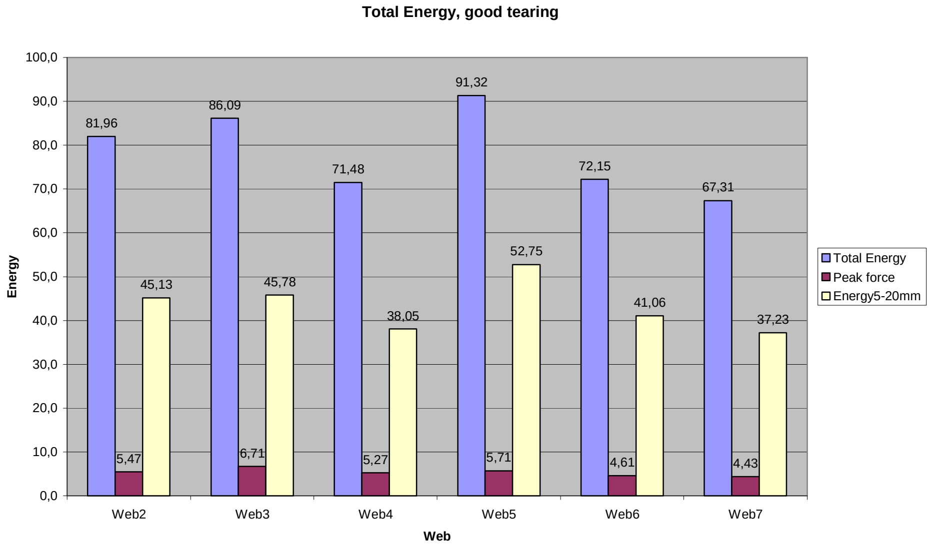


Figure 41 - Bar chart "good" samples

In Figure 42 one can see the Average Force and the Energy/cell values for all 6 webs measured. The Average force is a measurement of the average force needed after the peak and the Energy/cell intends to specify the value needed to break one cell, see *5.4.2 Following tearing*.

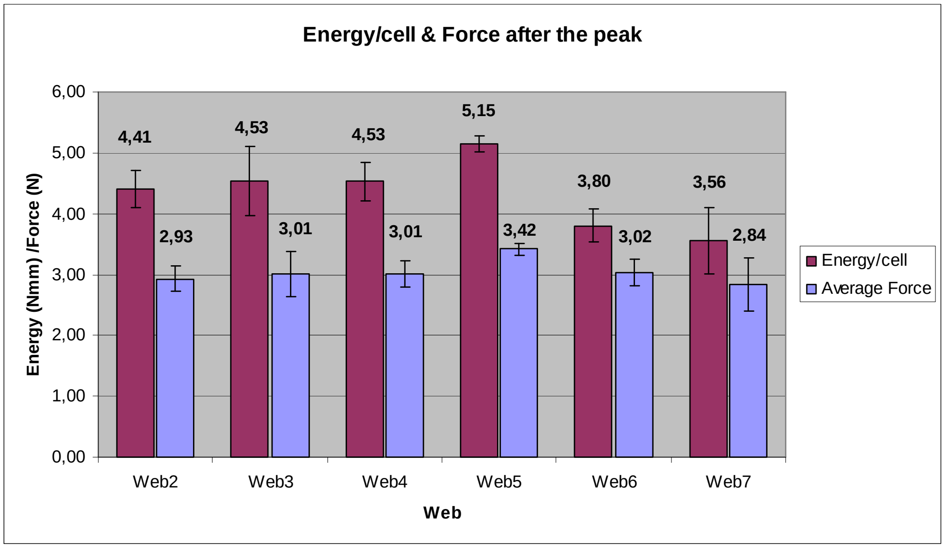


Figure 42 - Average force

5.3.4 Tensile or Tear breakage

The five upper curves F1-F5 in Figure 43 is the measured force F during the test. By calculating the difference in angle α between the start and end of the test and spreading it out over the 300 measurement points during tearing of the perforation the force F_n1-F_n5 have been obtained and are shown below the F curves. This is a fairly steady curve showing the force needed to break bridges during the lapse.

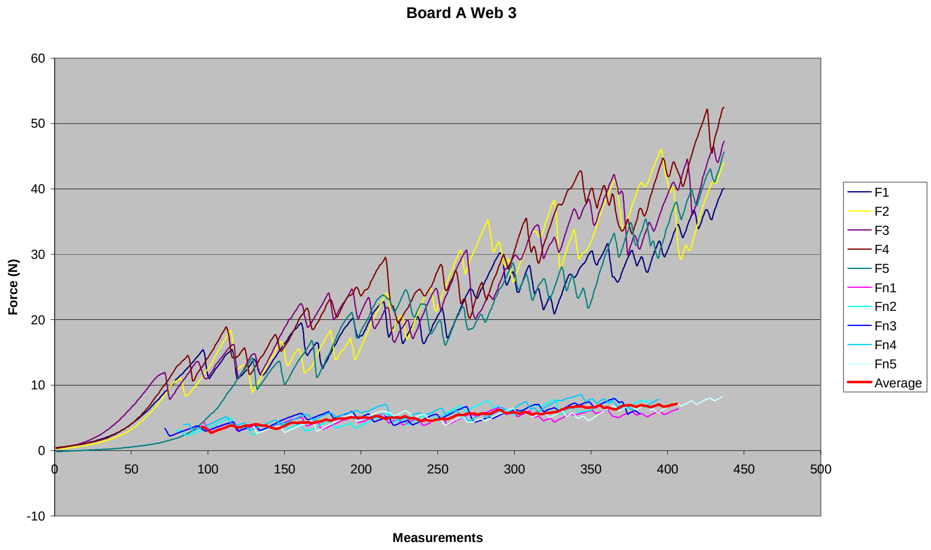


Figure 43 - Y tear plot board A web 3

Average plots of the four variants show that material produced by the light knives is harder to tear than material produced by standard knives, exactly as it should be and the difference between A and B boards is not significant but present.

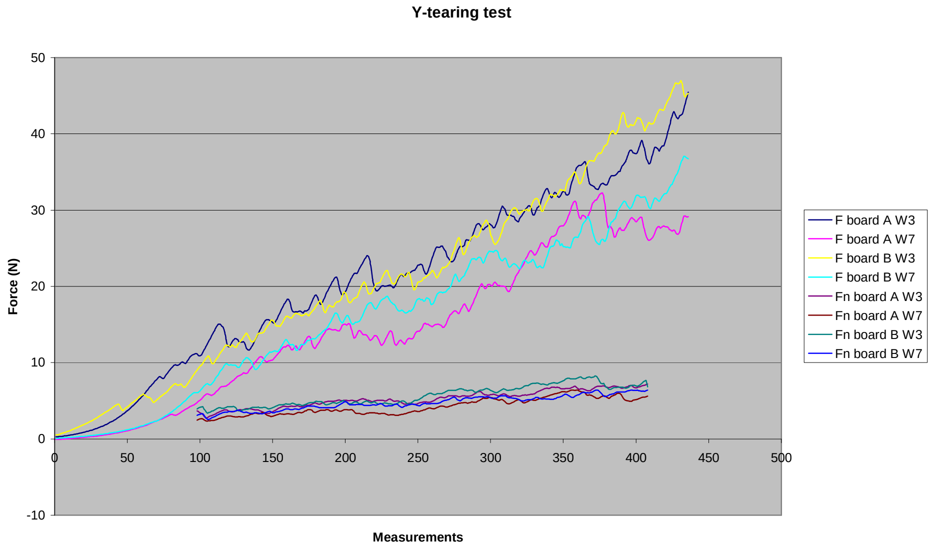


Figure 44 - Y-tear average plot

When looking only at the F_n plots in Figure 45 one can see that they vary a little more than seen in Figure 44. Considering that it is the measurements in the beginning of the curve that is most applicable, until the twisting of the sample disturbs the measurement, the force is stable enough to be considered as constant around 4 N or just below.

Figure 45 - F_n plot in Y-tear

When breaking the perforation with the tensile method the result is slightly different. As in the Y-tearing test the measured force is stable during most of the perforation breaking procedure which is good. The results from each variant looks like Figure 46 and by choosing a part in the middle of the curves and calculating the average result shown in Figure 47 is achieved.

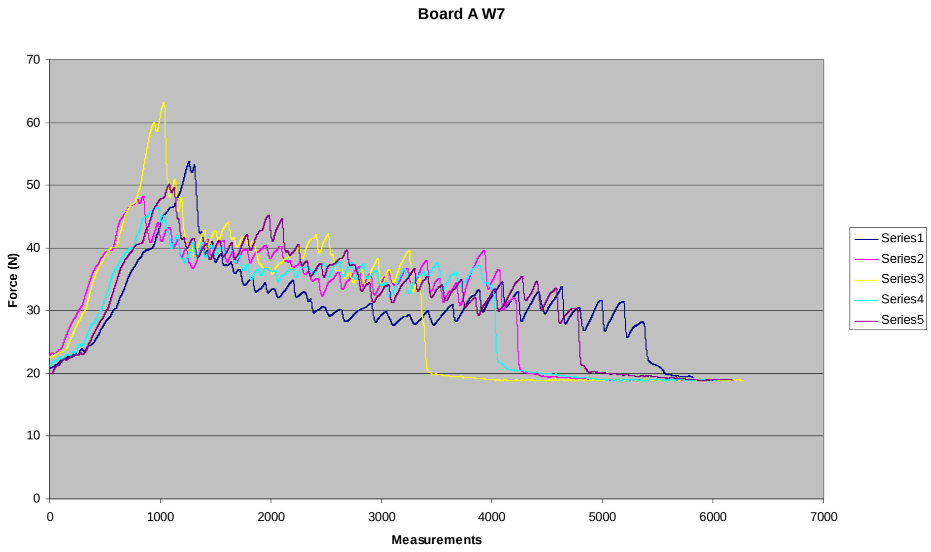


Figure 46 - Tensile breakage perforation

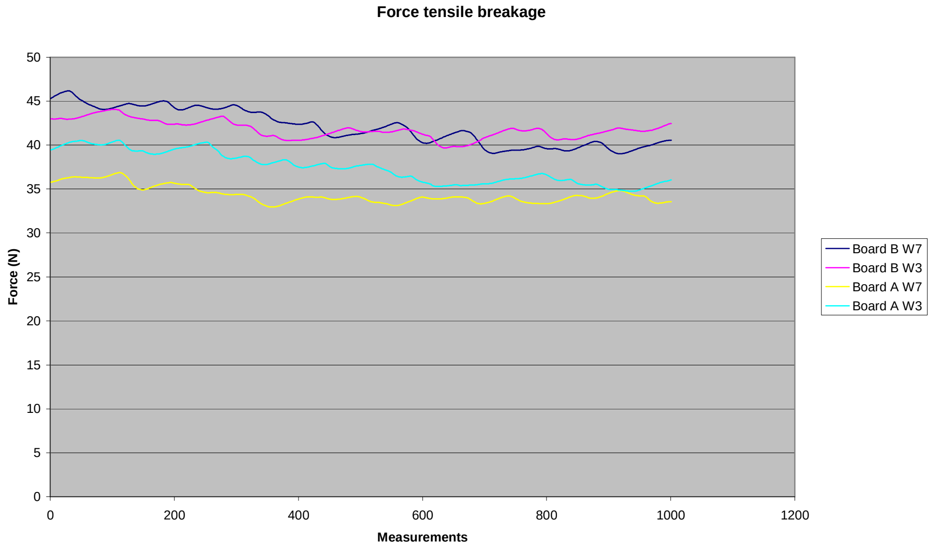


Figure 47 - Average tensile breakage force

Once again one can see that the B board needs higher force to break and at least in the A board the difference between light and standard knife is significant. The force needed significantly higher in tensile breakage where the average force for the different knives and boards vary between 35-45 N.

5.3.5 Microscope investigation

In Figure 48 and Figure 49 one can see pictures of cracked bridges that show the remaining fibers. The most significant difference is the fiber size between B and A boards.

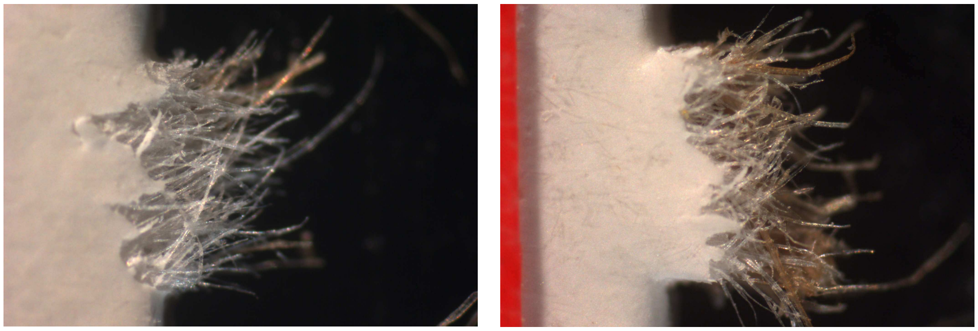


Figure 48 – Broken bridges board A, tensile (left) and tear breakage (right)

One can not see any major difference between the bridges cracked by tearing or tensile force.

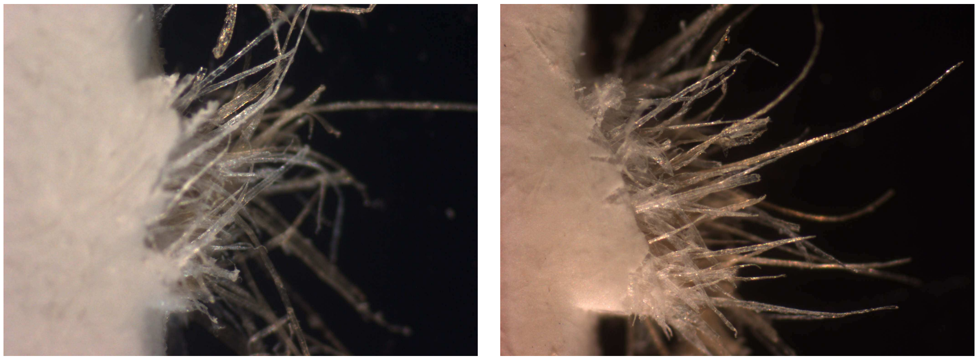
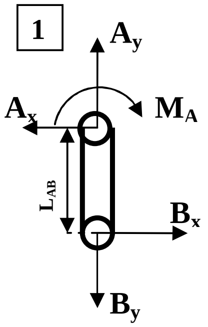


Figure 49 – Broken bridges board B, tensile (left) and tear load(right).

B material has more remaining long fibers that have been pulled out instead of being broken.

5.3.6 Process description

Free body diagrams are made for all parts to specify the forces and momentums that are present to get a clear picture of the case. The force A_y in Figure 50 is the same as the measured force F during the test.



$$\uparrow: A_y - B_y = 0$$

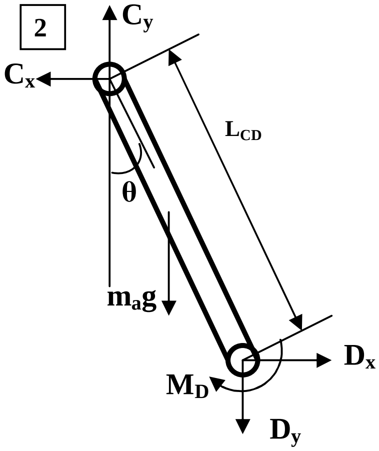
$$A_y = B_y = C_y = F$$

$$\rightarrow: B_x - A_x = 0$$

$$B_x = A_x$$

$$\overrightarrow{M}_A : M_A - B_x \cdot L_{AB} = 0$$

Figure 50 - Upper link



$$\uparrow: C_y - m_a g - D_y = 0$$

$$D_y = F - m_a g$$

$$\rightarrow: D_x - C_x = 0$$

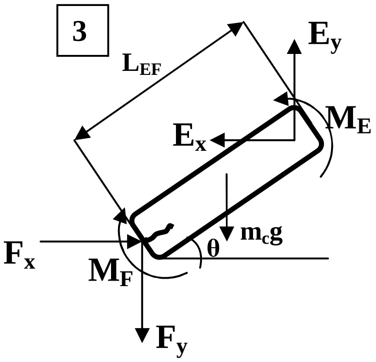
$$\overrightarrow{M}_D : M_D - C_x \cdot L_{CD} \cdot \cos\theta - m_a g \cdot \frac{L_{CD}}{2} \cdot \sin\theta + C_y \cdot L_{CD} \cdot \sin\theta = 0$$

Figure 51 - Swinging arm

$$\uparrow: E_y - m_c g - F_y = 0$$

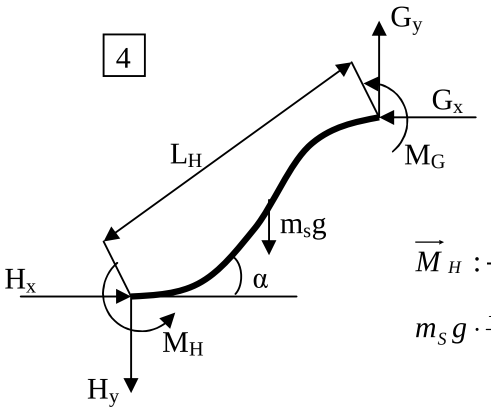
$$F_y = F - m_a g - m_c g$$

$$\rightarrow: F_x - E_x = 0$$



$$\overrightarrow{M}_E : -M_E + M_F - F_x \cdot L_{EF} \cdot \sin\theta - m_c g \cdot \frac{L_{EF}}{2} \cdot \cos\theta - F_y \cdot L_{FE} \cdot \cos\theta = 0$$

Figure 52 - Lower part of clamp



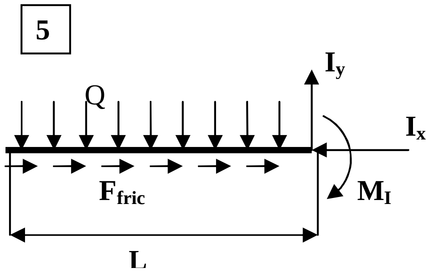
$$\uparrow: G_y - m_S g - H_y = 0$$

$$H_y = F - m_a g - m_c g - m_s g$$

$$\rightarrow: H_x - G_x = 0$$

$$\overrightarrow{M}_H : -M_G - M_H - G_x \cdot L_{HG} \cdot \sin\alpha + m_S g \cdot \frac{L_{HG}}{2} \cdot \cos\alpha - G_y \cdot L_{HG} \cdot \cos\alpha = 0$$

Figure 53 - Torn perforation



$$\uparrow: I_y - Q = 0$$

$$\rightarrow: F_{fric} - I_x = 0$$

$$\overrightarrow{M}_I : M_I - Q \cdot \frac{L}{2} = 0$$

Figure 54 - Clamped part of perforation

Looking at the equation systems for all parts one can see that there are always more unknown factors than formed equations which means that the system can not be solved in a simple way. When looking at an instant of the lapse some of the factors are possible to decide and measure.

Measured value:
F – measured during the whole lapse.
Fixed values:
$m_c + m_a$ – 3,4 N
m_s – The mass of the torn part of the perforation ≈0
L_{AB} - 0,02 m
L_{CD} - 0,224m
L_{EF} - 0,048m

Board stiffness related values:
θ – The value of the angle decreases during the lapse and with lower board stiffness.
α – The value of the angle decreases with higher board stiffness.
L_{HG} – Depends on how far in to the test one has come.

As the stiffness of the board seemed to affect the tearing one decided to evaluate the difference between θ and α for different material stiffness's. Three different boards were torn and pictures were taken to analyze the angles and shape of the torn part. Figure 55 to Figure 57 shows the same part as described in Figure 53. One can see how α increases with lower board stiffness which affects the force and momentum acting on the point where the perforation bridge is torn. The angle θ, which is between the clamp arm and the vertical, decreases during the lapse and with a higher α.

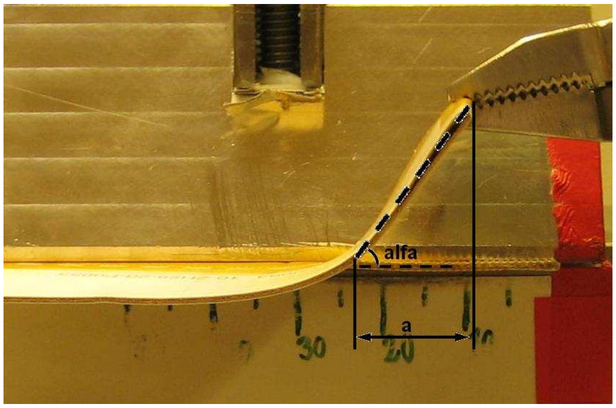


Figure 55 - 320 mN board

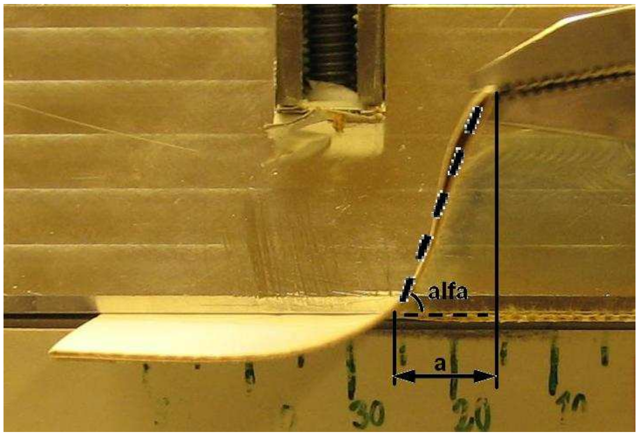


Figure 56 – 80 mN board

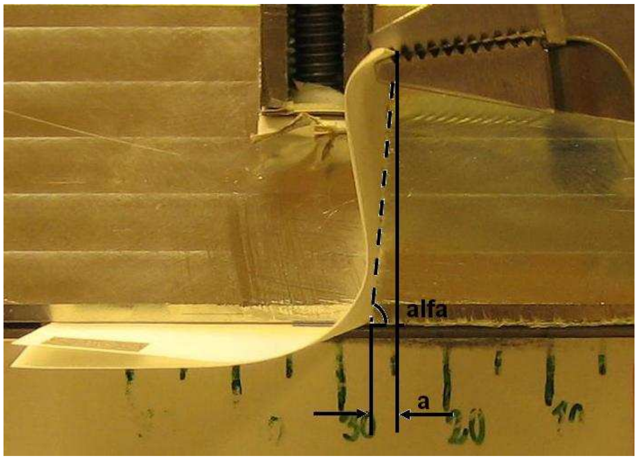


Figure 57 – 0 mN board

5.4 Analysis

A perfect tearing, done by the mechanical tearing method described in *4.3 Measuring procedure*, gives us a graph like Figure 33 on page 39. It begins with a major peak followed by a rather straight line describing the force needed to break all the following bridges of the perforation. In good cases it is even possible to find out the number of broken bridges by counting the number of minor peaks in the graph. The analysis of the performed test is done by going through the resulting graph's different sections and phenomenon.

5.4.1 Energy peak

The height and width of the peak can vary a lot and it describes the force needed to initiate the tearing. There are several reasons for the variation and they come from both the material and the test equipment.

When the material is clamped along the folded edge several bridges has to be torn at the same time. Later during the tearing it is maximum 2 bridges at a time, one on each side, to tear but in the initial phase it is most likely more which increases the force needed. To have as little variations as possible between the samples one needs to clamp at the same place every time.

By folding the packaging material the possibility of human interference increases. When tearing a package by hand the look of the folded edge of the perforation probably have a major impact. If there is a perforation cut on the folded edge there will be easier to focus the applied force to break the following bridge. When the perforation is torn mechanically this influence is much less according to *5.3.2 Starting with cut or bridge* results. The upper clamp that holds approximately 2 mm of material will tear more than one bridge simultaneously when tearing begins and ease this affect compared to human tearing. As seen in Figure 37 on page 41 the Peak load difference is less than 5 % between samples with and without a cut where the tearing begins. That can not be seen as significant and this is how the conclusion is drawn that we can not compare the affect of cut or bridge in the beginning the perforation with mechanical tearing.

When looking at an open package and how it has been clamped we can see how it appears to have double thickness in the folded area, seen in Figure 58. This makes it tougher to tear and increases the Peak load compared to one side tests.

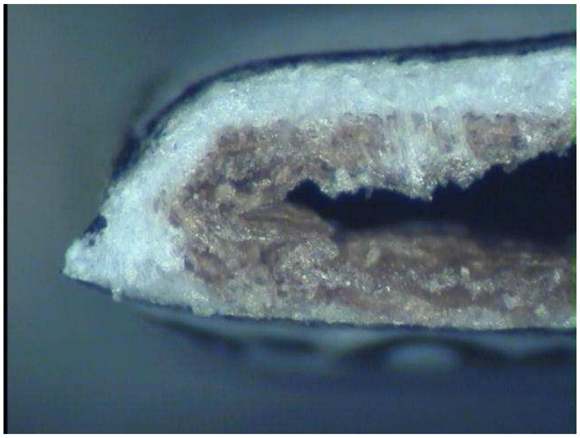


Figure 58 - Picture of the folded edge showing its double thickness

In the initial phase of the tearing the material between the two clamps, approximately 1mm wide as seen in Figure 23 on page 29, is stretched and it is within the paperboard's elastic region. When the angle of the slope is changed closer to the top of the peak the material starts to deform plastically. When the top is reached the material has undergone both elastic and plastic deformation but tearing is not initialized yet. The energy put into the system until the peak load is reached both deforms the material and is stored within the system. This stored energy is released as soon as tearing is initialized which cause a major drop of

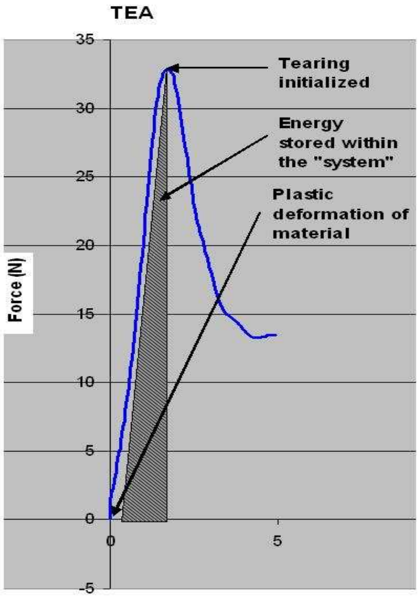


Figure 59 - Energies within the peak

force. The higher peak there is the more stored energy is available to start the tearing and the steeper the drop will be. The height of the peak is not proportional to the following force or energy needed to continue the tearing. The ability to store energy within the system depends on its rigidity and stability. Elastic material can store more energy than stiff material and each joint between the load cell and the perforation that does not fit perfectly will affect the energy storing possibility. The width of the peak is decided by the possibility for the material to deform plastically and if the breakage is tough or brittle. The amount of material between the clamps has a big impact on this result.

Here one can see how the height of the peak change the drop of the force but all three samples gather together afterwards and the tearing continues with similar forces regardless the variation in Peak load, i.e. the Peak load does not explain the openability during the rest of the tearing.

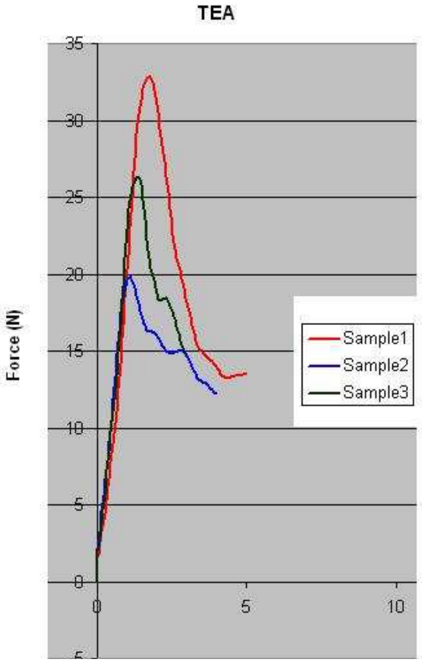


Figure 60 – Different peak heights

5.4.2 Following tearing

In the perfect conditions, where the perforation line is followed during the tearing, the force needed to tear the following bridges is stabilizing only shifting up and down for every cracked bridge, and the same average force is needed during the rest of the tearing. If the tearing chooses another direction outside the perforated line the second part of the graph will be less consistent and the force value will increase towards the end. This will also be the case if the material starts to delaminate and the different board layers are torn apart during tearing.

To be able to get a more detailed picture of the tearing force than the total energy, as well as exclude the varying Peak load affecting the energy to peak, the part of the curve after the peak has to be measured separately. After analyzing result in *5.3.2 Starting with cut or bridge*, as well as the high speed video recording it is decided that between 5 and 20 mm in vertical tearing distance there is approximately 10 or 12 bridges torn along the perforation depending on knife type. To be able to get a more precise measurement the energy per cell is calculated. A cell consists of one bridge and one of the cuts located next to it. The average force needed to continue the tearing after the peak is also measured. According to Figure 42 on page 44 one can see that the average force does not vary much and only changing in the web 5 with the partial cut and web 6-7 perforated with standard knives.

As a conclusion from the initial tests there is a need to make more measurements than Total energy, Peak load, and Energy to peak to bring out more information from the collected data. In following tests complementing values will be measured as described in number 1-4.

1. **Energy 10-20mm:** A value which is an energy measurement that is not affected by the varying initial peak. Changed from 5-20mm when folded packaging material is used instead of one side printed board.
2. **Energy/cell:** The Energy/cell is achieved by taking the "Energy 10-20mm" and divides it by the number of cells torn during this distance.
   Light knife: 7 bridges, Standard knife: 8.5 bridges.
   With this measured value one can compare light and standard knife values.
3. **Average force:** The average force needed during the interval of 10 to 20 mm.
4. **End average force:** The average force in the end of the lapse which is often increased due to polymer elongation if the sample is not torn along the perforation.

Together with these measurements one can use quotas between the measurements to compare samples. One used is for example End Force / Average Force to see how much the force increase in the end of the curve due to e.g. polymer elongation.

5.4.3 Breaking Modus

The results show that the force needed to tear a bridge is much less than the force needed to crack it by tensile force. Of course one can question if 100% Modus I and III have been achieved but something that confirms the result is the internal relationship between boards and knives which are the same in both cases comparing Figure 45 and Figure 47 on page 46, 47 . The difference in force needed is approximately 10 times and what is the reason?

Looking at the difference between the two force-approximations described in Figure 32 on page 37 one realizes that this is one of the reasons for the big difference. A more linear force distribution in the tensile load case increase's the measured force. One can also see that it can not be the only difference when looking at the measured force in the tensile case. When tearing the last bridge one still has to apply a 30 N force according to Figure 46 on page 47 and then the force distribution act on only one bridge and have a nonexistent impact. Something to have in mind is that by doing RTS test explained in *3.5.2*

Material weakening by perforation the force needed to pull one bridge at a time is varying between 15-20N for this type of board and knife set up.

The more exponential the force distribution in the tear test is estimated to be the more of the measured force is focused on the breaking bridge. One can see that there is a change in the measured force after the half lapse and the force distribution can be the reason. The perforation is 35mm long and if it is estimated that the exponential distribution stretch half of the perforations length this force reaches the un-perforated board after the half lapse. This will increase the measured force due to the increased strength of un-perforated board.

When looking at the microscope pictures there was no significant difference between tear and tensile breakage. One can then assume that it is not the number of pulled out or broken fibers that creates the force difference according to *3.1.6 Board breakage.*

When the force distribution or fiber breakage can not explain the difference the next reason to evaluate is the difference of how the force is acting on the material. When tensile load is used the force is only acting within the x-y plane which is the cross- and machine directions of the board. In these directions the strength is varying between 7 and 20 kN/m with the lowest strength for board A in cross direction. If the thickness of the board is considered the strength is calculated to 25-70 N/mm^2. The out-of-plane Z-strength, in the thickness direction, is 100 times lower and around 0.5 N/mm^2. The shear force a board is able to resist is also much lower than MD-strength and around 1.1 N/mm^2. Considering this one can assume that the applied force acts slightly in the out of plane Z-direction during Y-tearing as well as shearing the material instead of pulling it apart which cause’s the force difference.

The goal with the test is to be able to estimate which kind of Modus that is used during mechanical tearing by comparing the average forces. To be able to compare the same material one has to go back to *5.3.3 Single side printed board* which is the result from tearing similar material as above by using the mechanical tearing method. By studying Figure 38 on page 42 one can see that a force around 3 N is needed which is even slightly lower than the force used in Y-tear seen in Figure 45 on page 46. By considering this one can decide that also during mechanical tearing some part of the force is acting in the weaker Z-direction out of the stronger X-Y –plane. Both the mechanical tearing method and Y- tearing are according to modus III.

5.4.4 Process description

By investigating all forces within the system in the free body diagram it is easier to understand how the measured force F together with a momentum acts on the perforation.

Looking at the equations for Figure 53 it is possible to derive some conclusions about the force H_y and momentum M_H acting to tear the bridge.

$$H_y = F - m_a g - m_c g - m_s g$$

$$M_H = -M_G - G_x \cdot L_{HG} \cdot \sin\alpha +$$
$$m_S g \cdot \frac{L_{HG}}{2} \cdot \cos\alpha - G_y \cdot L_{HG} \cdot \cos\alpha$$

As $m_s \approx 0$

$$M_H = -M_G - G_x \cdot L_{HG} \cdot \sin\alpha - G_y \cdot L_{HG} \cdot \cos\alpha$$

As the measured force always is zeroed with the clamp hanging freely one has already compensated for the mass of m_a and m_c. As said earlier m_s can be seen as 0 due to its small size.

$$H_y = F$$
$$H_x = G_x = F_x = E_x = D_x = C_x = B_x = A_x$$

$$M_H = -C_x L_{CD} \cos\theta + C_y L_{CD} \sin\theta + F_x L_{EF} \sin\theta + F_y L_{EF} \cos\theta -$$
$$G_x \cdot L_{HG} \cdot \sin\alpha - G_y \cdot L_{HG} \cdot \cos\alpha$$

$$M_H = (F_y L_{EF} - C_x L_{CD})\cos\theta + (C_y L_{CD} + F_x L_{EF})\sin\theta -$$
$$L_{HG}(G_x \sin\alpha + G_y \cos\alpha)$$

The force H_y is not affected by the angles α and θ and by that not the board and its stiffness. The momentum M_H is affected by α as seen in Figure 55- Figure 57 on page 51. Measured values of α together with calculated values of θ have been a foundation of a linear relationship between α, θ and the momentum M_H. Plots of this relationship can be seen in *Appendix F*.

5.5 Summary Qualitative tests

When summarizing the first investigation new knowledge of the process has been established. First of all the energy peak does not tell us more about the material than what force that is needed to initiate the mechanical tearing. If this force correlates with the toughness a person feel to begin the tearing is unknown. The peak is also most affected by how samples are mounted which is a problem when measured values are compared.

The part of the curve after the peak is more affected by the material than how the sample is mounted but there is a need to achieve a more specific measurement than there is today. The energy after the peak, energy/cell, and average force are possible measurements that will be evaluated in the next chapter.

When tearing the sample by using mechanical tearing one is very close to tearing and not pulling. The difference in force between Y-tearing and mechanical tearing is very little and distinguish to tensile breakage that has a 10 times higher force. The lower force in tearing compare to tensile breakage is due to that the force is not only in the stronger MD/CD but also in Z-direction which has much less tensile strength. There are no significant differences, which can be seen with a microscope, between the number of broken or pulled out fibers in either tear or tensile breakage.

When looking at the forces acting within the process, seen in *5.3.6 Process description,* one can determine that the vertical force acting on the breaking bridge, measured by the load cell, is not affected by parameters as α and θ related to board stiffness.

6 Quantitative tests

This chapter contains the second and major part of tests within this thesis with a quantitative approach testing enough material to get a statistical approved result.

6.1 Test description

This part of the thesis should evaluate the material tested and correlate the measurements done by mechanical tearing with both process- and material parameters as well as the result from the openability test showing the true values of openability. There is also a need of testing the method itself which is done by a Repeatability and Reproducibility test together with a factorial experiment revealing which of the material parameters that affect the measured values the most.

6.1.1 Openability test

As mentioned earlier one of the objectives for this work is to say if mechanical tearing can be used to classify material regarding openability. Today's method of testing openability implies that 300 packages for each test is filled and opened by hand. Each package is classified in one of four categories depending of the amount of polymer residues covering the hole as in Figure 15. As well as in mechanical tearing no pre-folding of the perforation is allowed and as similar tearing procedure as possible should be used all the time and by everyone opening. Table 3 shows the test plan for this test containing which variants and webs that are tested.

Table 3 - Samlpes Openability test plan

		Variant 1	Variant 2	Variant 3	Variant 4	Variant 5
Adhesion		High	Low	High	Low	Low
PE-strength		Low	Low	High	High	High
Board		A	A	A	A	B
Packages						
web 1:	Light 0.00				x	
web 2:	Light -0.02					
web 3:	Light -0.06	x	x	x	x	x
web 4:	Light -0.00	x	x	x	x	x
web 5:	Light+0.08	x	x	x	x	x
web 6:	Stn 0.00				x	
web 7:	Stn-0.06		x		x	

This test is performed in Thailand and packages are filled with water and opened after 24h of storage in 23° C and 50% air humidity. The filling machine used is a TBA/19 010V placed at a customer site outside Bangkok.

6.1.2 Tearing Energy Absorption test

During the main test as much as possible of the material produced in Singapore week 40 is tested using the mechanical tearing procedure. The test follows the test description according to chapter *4.3 Measuring procedure* and measurements done are the one that came out from the previous qualitative tests shown in *5.4.2 Following tearing.* Five different variants and seven different webs are tested which means 35 variants. As the method specifies 15 samples of each test is prepared and the first 10 that tears well are used. As long as the sample does not break its result is used even if the perforation is not followed.

Table 4 – Tearing Energy Absorption test plan

	Variant 1	Variant 2	Variant 3	Variant 4	Variant 5
Adhesion PE-strength Board	High Low A	Low Low A	High High A	Low High A	Low High B
PM					
web 1: Light 0.00	*X*	*X*	*X*	*X*	*X*
web 2: Light -0.02	*X*	*X*	*X*	*X*	*X*
web 3: Light -0.06	*X*	*X*	*X*	*X*	*X*
web 4: Light -0.00	*X*	*X*	*X*	*X*	*X*
web 5: Light+0.08	*X*	*X*	*X*	*X*	*X*
web 6: Stnd 0.00	*X*	*X*	*X*	*X*	*X*
web 7: Stnd -0.06	*X*	*X*	*X*	*X*	*X*

An Excel macro is created to make the data handling as convenient as possible and all data is stored in a result database created to gather as much information as possible regarding each variant and sample. It contains all measurements from the TEA test as well as material- and process parameter, quality control measurements of raw paperboard and results of measurements done by the quality assurance lab in Jurong, Singapore. This database then contains all data ready for further analysis with multivariate tools.

As a part of this test printed board material, without foil and polymer, is also tested by tearing. This is done for both board A and B for 5 webs and 5 different engagements.

Table 5 - Test plan printed board

Board		A	B
	Knife / E		
web 1:	Light 0.00		
web 2:	Light -0.02	*x*	*x*
web 3:	Light -0.06	*x*	*x*
web 4:	Light -0.00	*x*	*x*
web 5:	Light+0.08	*x*	*x*
web 6:	Stnd 0.00		
web 7:	Stnd -0.06	*x*	*x*

6.1.3 Laboratory tests and measurements

Four different test results from the Singapore factory are used in the database, RTS (Relative Tensile Strength) for coated and uncoated material, and Adhesion between the foil and inside as well as foil and Polyethylene. In RTS measurements the relative strength of material with and without perforation is measured in a tensile test pulling a 15mm wide sample.

Adhesion is the force between the different layers of polymer and the foil. It is measured by peeling of the polymer and pulling it away from the foil with a 180 degree angle and the average force needed is calculated. The foil-Inside adhesion is the most important when discussing openability and plastic residues.

6.1.4 Factorial test

The factorial test is done to try to define which of our key parameters that affect the measured values the most. Is it the perforation strength, adhesion or polymer strength that affects the total energy, average force etc. By using a high and a low level of the key parameters a test with 2^3 different materials are planned and the tested according to Table 7.

Table 6 - Factor and level discription

Factor		**Hi (+1)**	**Low (-1)**
A	**Adhesion**	High Line load pressure, low Die offset	Low Line load pressure, high Die offset
B	**PE-strength**	15% above specification	According to specification
C	**Perf. Strength**	Hard to open	Easy to open

Table 7 - Factorial test matrix

Material	**Web**	**A**	**B**	**C**	**AB**	**AC**	**BC**	**ABC**
Variant 2	**3**	-1	-1	-1	1	1	1	-1
Variant 1	**3**	1	-1	-1	-1	-1	1	1
Variant 4	**3**	-1	1	-1	-1	1	-1	1
Variant 2	**4**	-1	-1	1	1	-1	-1	1
Variant 3	**3**	1	1	-1	1	-1	-1	-1
Variant 1	**4**	1	-1	1	-1	1	-1	-1
Variant 4	**4**	-1	1	1	-1	-1	1	-1
Variant 3	**4**	1	1	1	1	1	1	1

Each of the eight combinations with changing A-C levels is tested 10 times to lower the impact of sample and measurement variations.

Four of the measured values are used as responses in this factorial test:

1. **Total Energy**
2. **Peak load**
3. **Energy 10-20mm**
4. **Energy/cell**

6.1.5 Repeatability and Reproducibility

When planning an R&R there are some steps to go through to make sure that the right decisions are taken regarding number of samples, operators' etc.[46].

1. **Calibration:** Calibration is done on a yearly basis and not within the test.
2. **Number of operators:** Two operators will be used to measure the operator to operator variation.
3. **Number of samples:** Eight samples are used in this test
4. **Sample selection:** Four out of 35 available materials are chosen. Two different knives within the revolution are used which result in (2*4=8 samples). Selected samples are chosen due to their low internal variation but with different characteristics covering an as wide span of the material range as possible.
5. **Number of trials:** Four trials for each operator
6. **Minimize sample variation:** Each sample contains perforations from the same knife in the revolution of seven.
7. **Measure individuals or average values:** Individual values are used.
8. **How to analyze the results:** Results are analyzed with Mini Tab, software used within Tetra Pak as well as in an Excel calculation template.
9. **One sided tolerances:** How to set tolerances are not easy due to the fact that there are not enough historical measurements to base them on and measured values are more to be seen as an indication of the perforation's tearing ability. Any how when looking at earlier measured data normal distributed one can see that 300±50 Nmm could be a good set-point. A chosen tolerance does not affect analyzed results which makes this less important.
10. **Measurement discrimination:** Measurement discrimination is very important and it is tested this time by using samples with different materials to make sure that the method is able to distinguish between these with its measurements.

Calculations of R&R are done on all responses to see if any of them showed a significant lower value making them more suitable to focus on.

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[46] Concepts for R&R studies (1991)

Table 8 - Sample overview R&R

Sample	Material	Knife	Engagem.	PE- strength	Die Offset	LLP
1	B	Light (1)	-0,02	High	High	Low
2	B	Light(2)	-0,02	High	High	Low
3	A	Stand(1)	0	Low	Low	High
4	A	Stand(2)	0	Low	Low	High
5	A	Light(1)	-0,06	Low	Low	High
6	A	Light(2)	-0,06	Low	Low	High
7	A	Light(1)	0,08	High	Low	High
8	A	Light(2)	0,08	High	Low	High

Table 8 shows how the eight samples are chosen and their specification. There are 4 different material specifications and knife engagements. The difference between (1) and (2) in the knife column is the different knifes in the revolution in the rolling cutting process but with the same settings. There should not be a significant difference between these two but by separating them one source of unwanted variation is reduced.

6.1.6 Multivariate analysis

The multivariate analysis is done by using SIMCA. The tool has been used on the database including all data from test *6.1.1 Openability test* and *6.1.2 Tearing Energy Absorption test* together with laboratory test and material descriptions. First of all a PCA analysis including all factors and variables are done to get an overview of the data. Then 14 PLS and OPLS analysis is performed, one for each measured factor (e.g Total energy and Openability sum), to see how good model one could achieve and if there are some correlations. Most of the work within SIMCA is done by Johan Nilsson, a former Umetrics employee working at Tetra Pak, but the analysis and conclusions are all made by the author. The goal is to see if any correlations between measure variables and openability can be found as well as which of measured variables that describes the phenomenon best. One also wants to know which of the input factors such as engagement, PE-strength etc that affect the results significantly

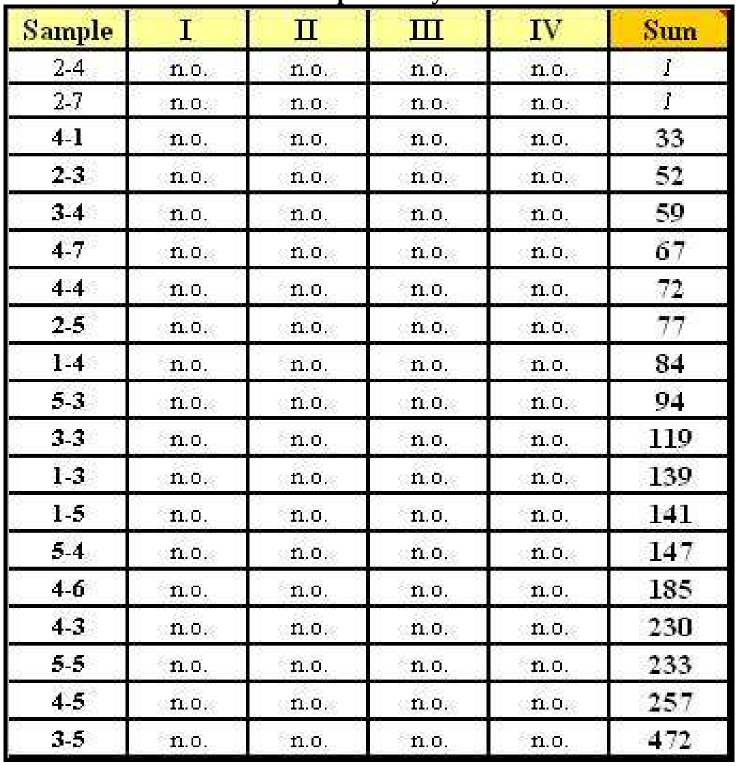
6.2 Quantitative results

In these measurements there are in most cases a lot of data stored that have been analyzed. In this part when the results are presented the data is left outside the report and only extracted information will be presented.

6.2.1 Openability test results

When the openability test was performed in Thailand the packages showed a lot of plastic residues on almost all variants and perforation engagements tested. The result shows the number of packages in each category after being opened and to calculate the openability sum weight factors for the different categories are used. Numbers printed in bold are outside the methods acceptance criteria.

Table 9 - Openability results



Sample	I	II	III	IV	Sum
2-4	n.o.	n.o.	n.o.	n.o.	*1*
2-7	n.o.	n.o.	n.o.	n.o.	*1*
4-1	n.o.	n.o.	n.o.	n.o.	**33**
2-3	n.o.	n.o.	n.o.	n.o.	**52**
3-4	n.o.	n.o.	n.o.	n.o.	**59**
4-7	n.o.	n.o.	n.o.	n.o.	**67**
4-4	n.o.	n.o.	n.o.	n.o.	**72**
2-5	n.o.	n.o.	n.o.	n.o.	**77**
1-4	n.o.	n.o.	n.o.	n.o.	**84**
5-3	n.o.	n.o.	n.o.	n.o.	**94**
3-3	n.o.	n.o.	n.o.	n.o.	**119**
1-3	n.o.	n.o.	n.o.	n.o.	**139**
1-5	n.o.	n.o.	n.o.	n.o.	**141**
5-4	n.o.	n.o.	n.o.	n.o.	**147**
4-6	n.o.	n.o.	n.o.	n.o.	**185**
4-3	n.o.	n.o.	n.o.	n.o.	**230**
5-5	n.o.	n.o.	n.o.	n.o.	**233**
4-5	n.o.	n.o.	n.o.	n.o.	**257**
3-5	n.o.	n.o.	n.o.	n.o.	**472**

n.o.=Individual numbers left out, since the sum of them is important for analyzing, while the individual numbers are not official.

One can see that there are only two accepted samples and they are web 4 and 7 from variant 2.

6.2.2 Tearing Energy Absorption test result

350 samples divided in 35 combinations of adhesion, perforation strength and polymer strength are tested and the result contains 7 different measured values together with 2 quotients, calculated for each sample explained in *5.4.2 Following tearing*. All raw data is treated in Excel to be able to present measured values together with plots of energy curves both as single values and averages. The measured and calculated single values from all 350 measurements are put into the database described in *6.1.2 Tearing Energy Absorption test.* The following result contains some of the graphs that has the most information and shows the most significant differences.

Figure 61 shows the average energy curve for each variant considering all seven webs. The five average curves for each variant is based on 70 tearing measurements each with a lot of internal variation. One can see that the curves differ from each other by board type in the beginning and by variant in the end. The B board in Variant 5 is on top until 10 mm and the four A variants begin to separate after the peak.

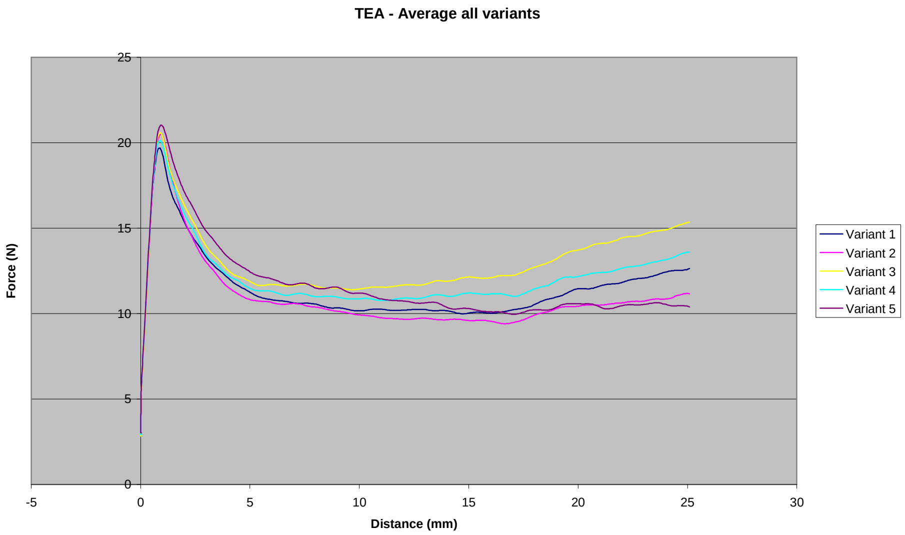


Figure 61 - Average all webs variant 1-5

Figure 62 shows the difference in the energy curve between all seven webs within variant two. These curves are based on 50 measurements each which one should have in mind. The peaks are shifting in height and when looking at the tearing 3 groups can be distinguished. Web 5 with the highest average force and energy, Web 2,3 and 4 which are in the middle and Web 6 and 7 with a lower average force.

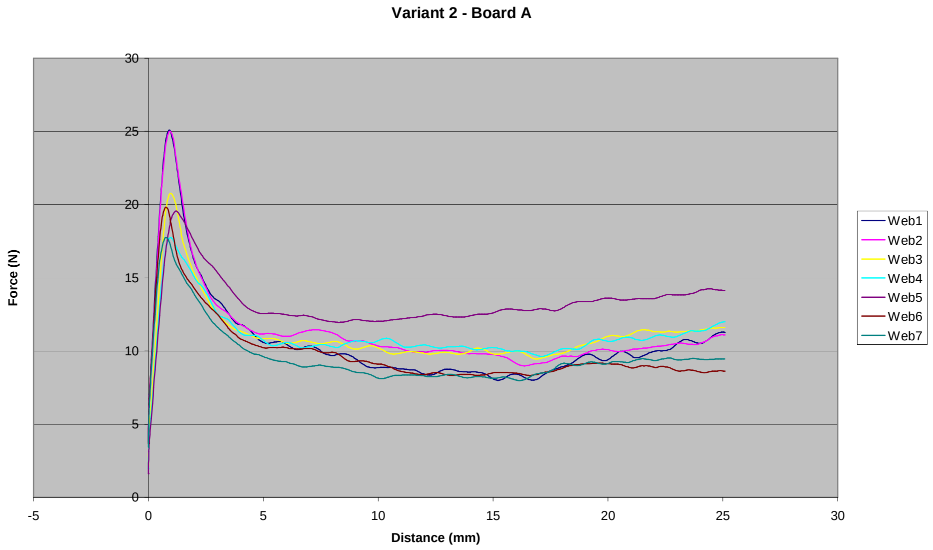


Figure 62 - All webs variant 2

Figure 63 is the same type of chart as Figure 62 but considering variant 3 instead which has higher inside grammage. The variation within this variant is much higher and even if the differences between the webs are bigger they do not follow the same pattern as in Figure 62. Web 5 is still above all others and web 7 the lowest one but in between there is a group with only web 3 pointing out.

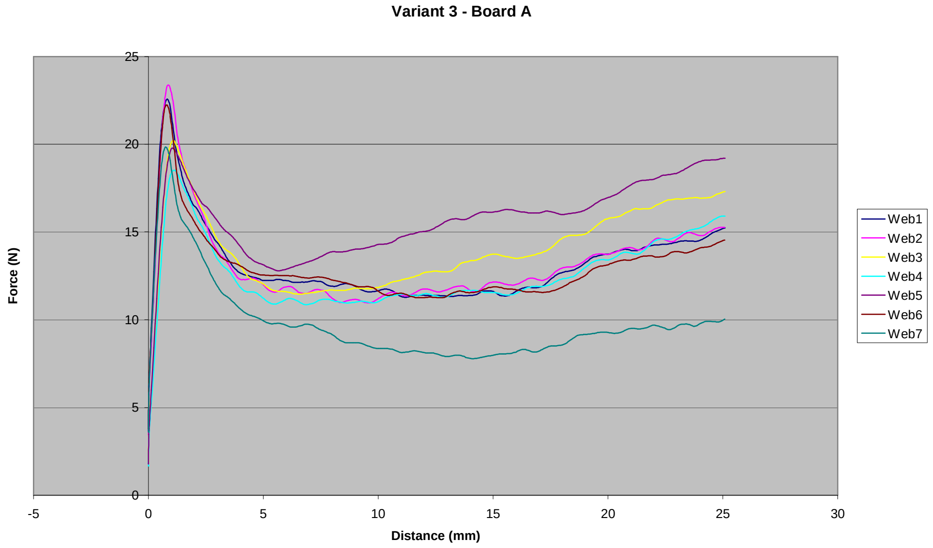


Figure 63 - All webs variant 3

Figure 64 handles the B board which is used in variant 5. This also has a high inside grammage but with a different result compare to Figure 63. It is still no doubt which curve that belongs to web 5 and one can also see that web 6 and 7 scores slightly lower than the other.

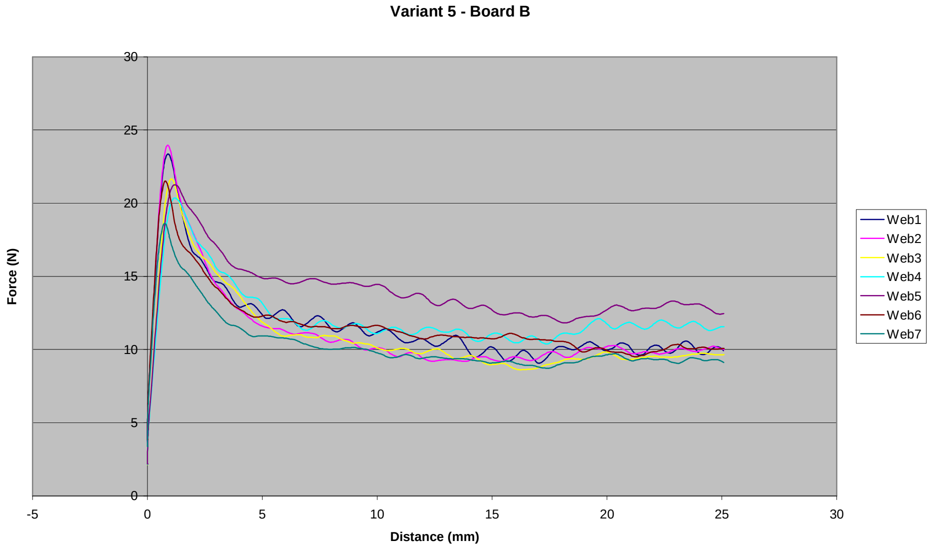


Figure 64 - All webs variant 5

In Figure 65 one can see two different graphs taken from the earlier figures. They are not only having very different appearance but they also have very different standard deviation. Each of them is based on 10 measured samples and material with higher energy and more elongating polymer has an increasing variation.

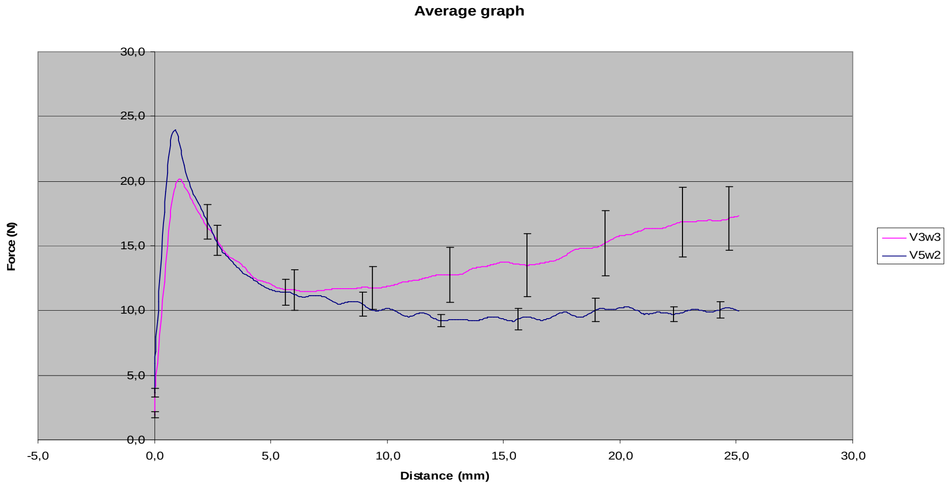


Figure 65 - Different graphs with standard deviation

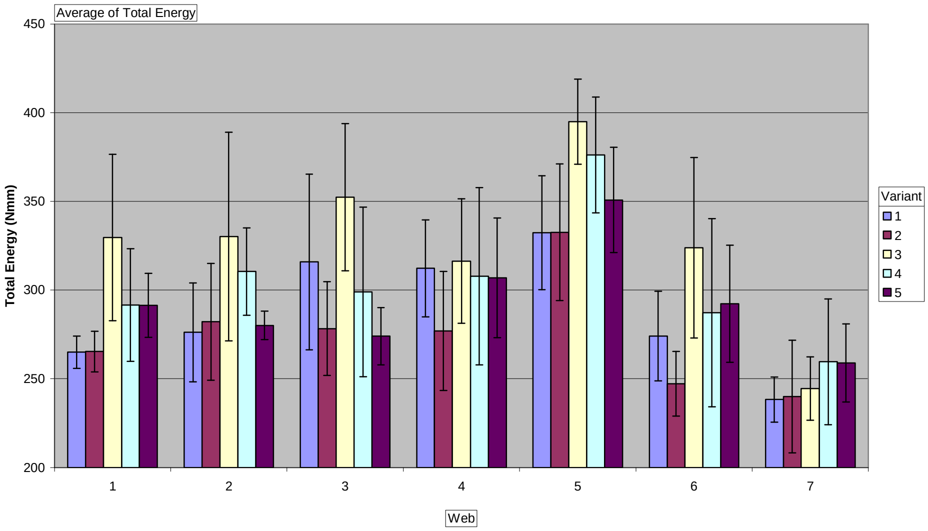


Figure 66 - Total Energy and std. deviation

Looking at Figure 66 one can see that the total energy differ a lot between web and variant. Web 5 has higher total energy and variant 3 rise above the other in all webs except for web 7. Each pile consists of the average value from ten measurements and the standard deviation is in many cases higher than the difference between webs and variants. Similar graphs for Energy/cell and Average Force can be found in *Appendix B* showing the same relationship between variants and webs as for Total energy in Figure 66.

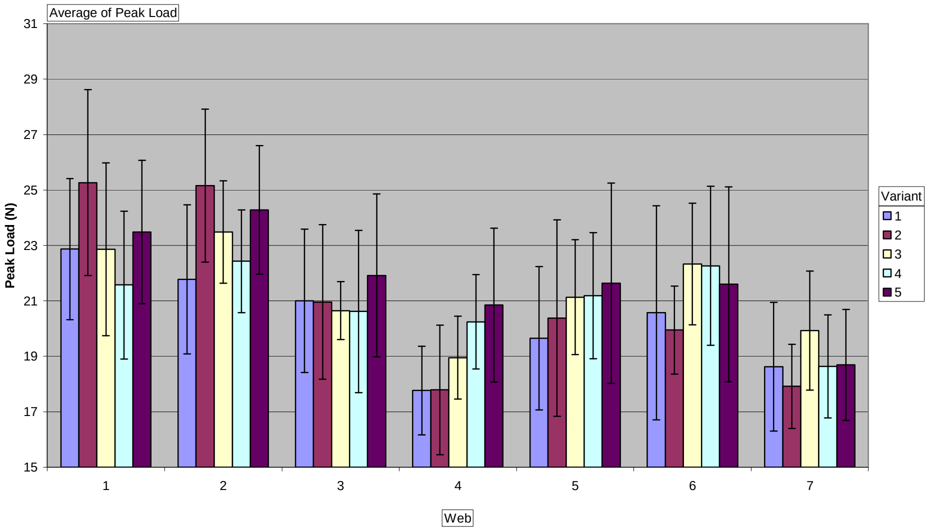


Figure 67 - Peak Load and std. deviation

When looking at the Peak load for all webs and variants, as for Total energy in Figure 66, one can in Figure 67 see that the relationship is not the same as for Total energy. No variant has a significant higher Peak load and web 1 and 2 scores highest in all variants. It is not possible to distinguish web 5 and the partial cut perforation from the others which would be desirable.

The results from the printed board tests, Figure 68 -Figure 69, is less dramatic then the laminated material. Without the impact from the polymer the variations are smaller and its only web 5 and web 7 that stands out significantly.

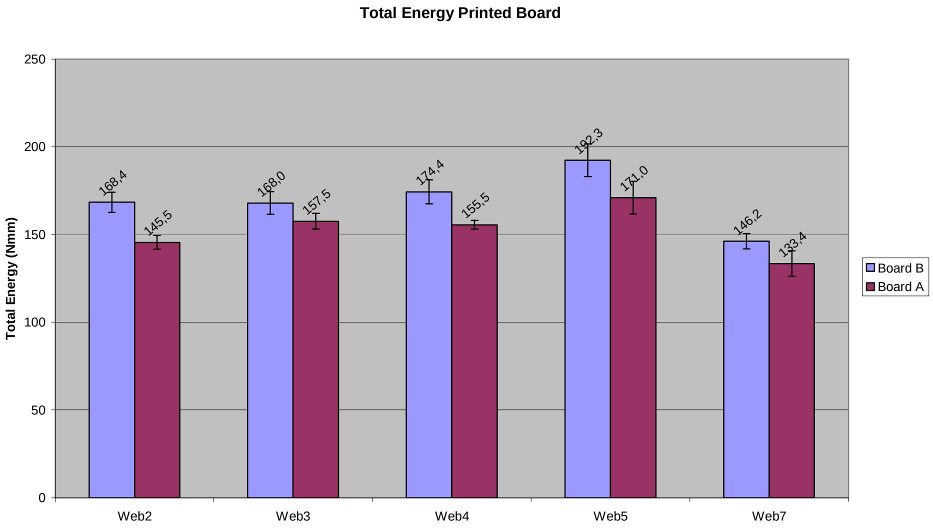


Figure 68 - Total Energy printed board

In the total energy chart one can see that board B constantly needs more energy to be torn and the standard deviation bars shows that the variations are small, between 3 - 10 % of the measured energy.

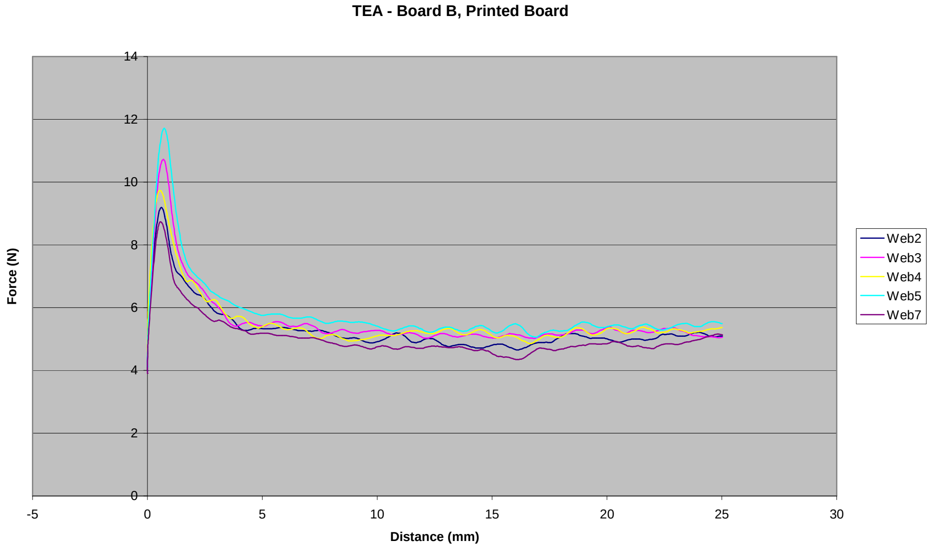


Figure 69 - A printed board

Looking at the graphs for printed board one can hardly see any difference and the behavior is as one could suppose with only web 5 rising above the others.

6.2.3 Results of laboratory tests and measurements

The adhesion and polymer weight of the inside polymer are measured by quality assurance laboratory in Singapore. The samples are collected after the lamination process. Earlier it is said that the adhesion always is worse for the middle webs due to the bending of the nip roller. By using new nip-roller technology one can see that this problem has been overcome and there is higher adhesion on the center webs. One can also see that there is no significant difference between the variants comparing to the difference between webs.

Table 10 - Adhesion measurements from Jurong.

Adhesion(N/m)	**Foil = Inside**	**Variant**	*1*	*2*	*3*	*4*	*5*
		1	*216*	*216*	*230*	*248*	*242*
		4	*262*	*260*	*281*	*280*	*271*
		7	*218*	*222*	*241*	*243*	*252*

6.2.4 Factorial experiment result

The result is presented with normal plots. In the normal plot the dashed lines represent ±3σ_{eff} and it is only values outside these limits that have a significant influence on the response. Results above the x-axis will increase the response when set on its high value and with the result below y=0 the response will decrease when the high value of the factor is used.

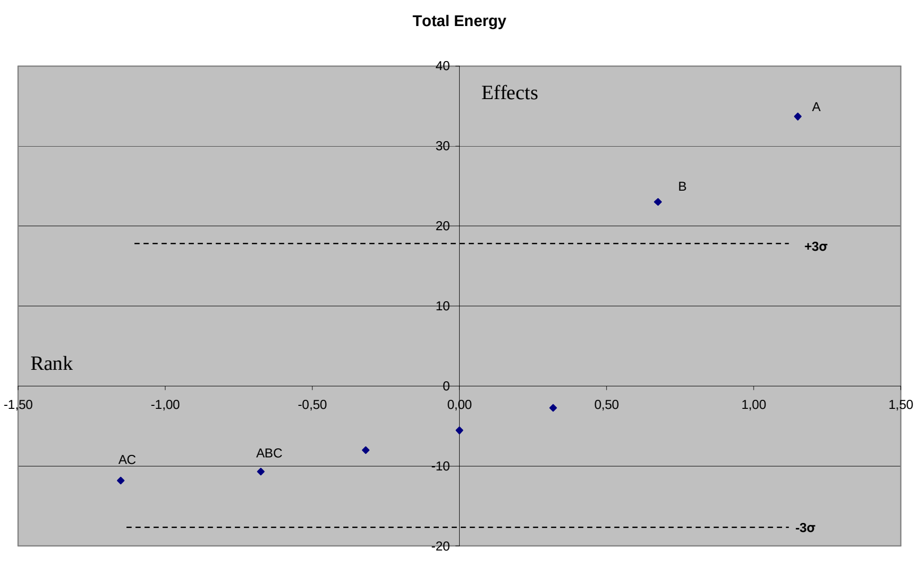


Figure 70 - Normal plot of Total energy effects

Figure 70 shows that it is only factor A, Adhesion and factor B, Polymer strength that has a significant impact on the measured Total energy. These factors will increase the Total energy if they are set on a high level. The normal plots for Energy 10-20 mm and Energy/cell are looking the same with rising responses for factor A and B at their high level. The Peak load has opposite relationship with the C factor significantly influencing the Peak Load. In this case the C factor is in the bottom of the chart which tells that with factor C at a high level the Peak load will decrease.

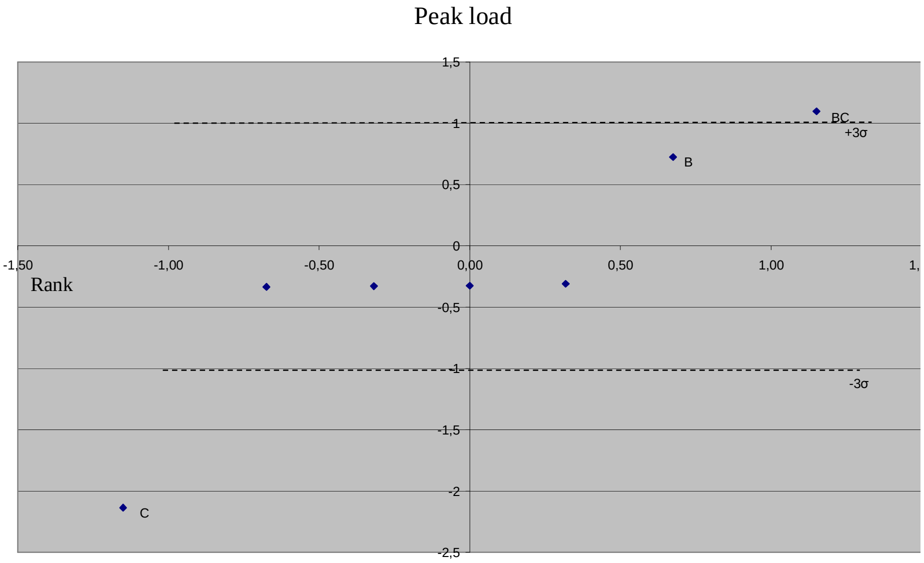


Figure 71 - Normal plot of Peak load effects

6.2.5 Repeatability and Reproducibility results

The tests were performed in a random order decided by MINITAB to minimize time effects on the result. The R&R calculations did not show any good results at all and the R&R index, that should be below 30% to be acceptable, is for this method 47% for the Total energy response and even worse for the others. As the result is such a disappointment one tries to investigate it closer to see why the result is so high and if there is any positive information to extract. As the Total energy was the response that did show the lowest R&R value it is the one further investigated.

Looking at the result produced by MINITAB in Figure 72 on page 73 it is possible to see that there is more of a relation between results than the high R&R value show. Looking at the R-bar chart, showing the variation between four similar samples measured by one operator, one can see that the difference between similar samples is large. The X-bar chart reveals the big part-to-part variation as well as one can see that the measured results are paired two and two.

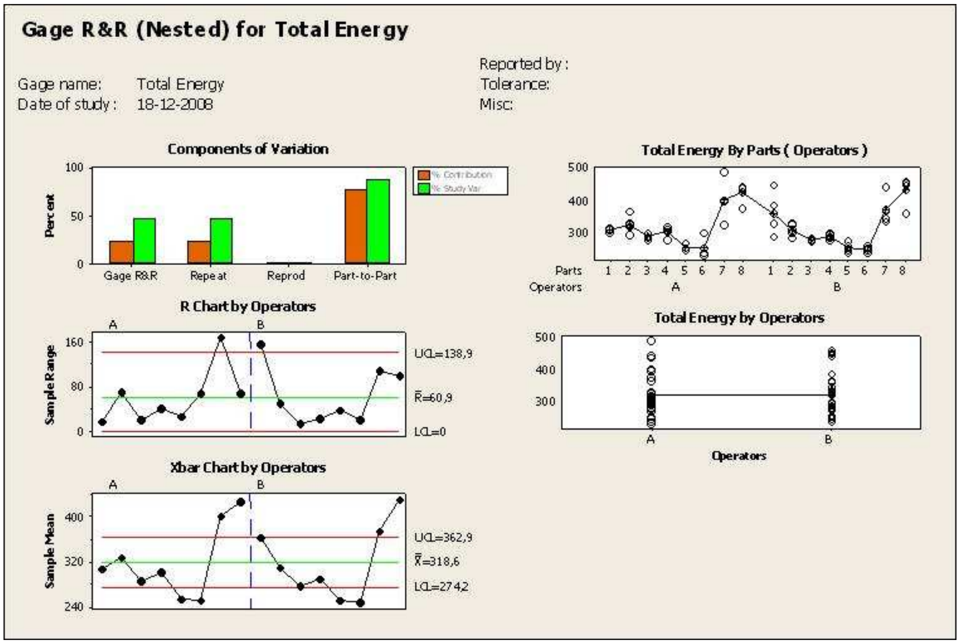


Figure 72 - R&R result Minitab

The average measured energy per operator is seen in the lower right picture and there is not much of a difference. In *Appendix C* and in top left picture in Figure 72 one can see how Reproducibility is set to zero. This is often the case when the test is destructive and it is a “nested” gage R&R. The top right picture shows a tendency for that higher total energy gives a higher R-value and a more uncertain process.

6.2.6 Multivariate analysis SIMCA, result

First of all a PCA analysis was performed to get a good overview of the process including all variables in the database. Looking at the model overview one can see that it takes fairly many components to achieve a satisfactory value of R^2 and Q^2 are just above 0,6 when 10 principal components is used.

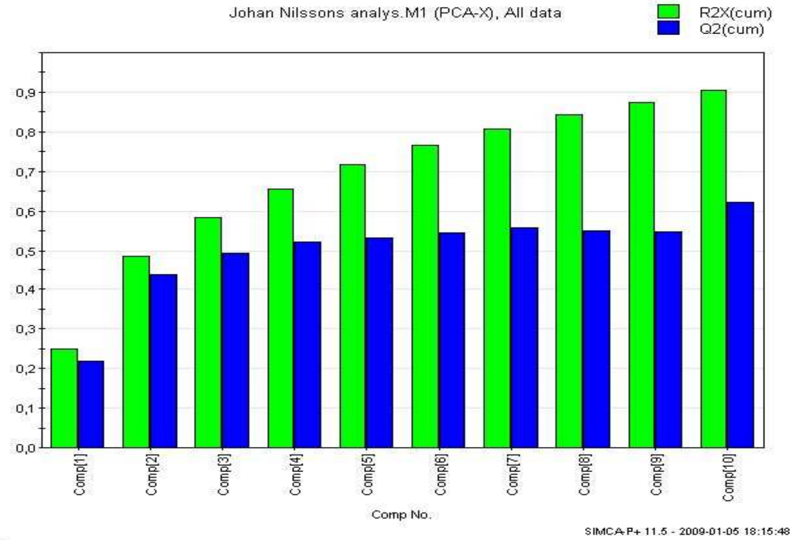


Figure 73 - Model Overview full PCA

If one would have continued with the PCA, four components would be the choice. In this case one chose to continue with PLS analysis instead. The overall PLS analysis including all components showed a low value of both R^2 and Q^2 which made us to try to model every response separately. The best result was achieved by an OPLS analysis which removes all variant of X that is orthogonal to Y. By doing this one managed to enhance the model's Q^2 value with up to 0.05 ending up with he best values for Total energy and Energy/ cell at 0.44 and 0.568 respectively. Other interesting values are Openability sum which has 0.3 and that Peak load once again does not score very well with 0.05 as Q^2.

Looking at the Total energy response it is modeled by 4+1 components with one X component orthogonal to Y. The first component explains most of the model and in Figure 74 one can see how it is affected by some input variables. The result is similar to earlier analysis and not surprising at all. The type of board used and their characteristics has a much lower impact than perforation and lamination parameters such as knife engagement and PE-strength. Line load pressure at high level increase the total energy and low level of Die offset does the same.

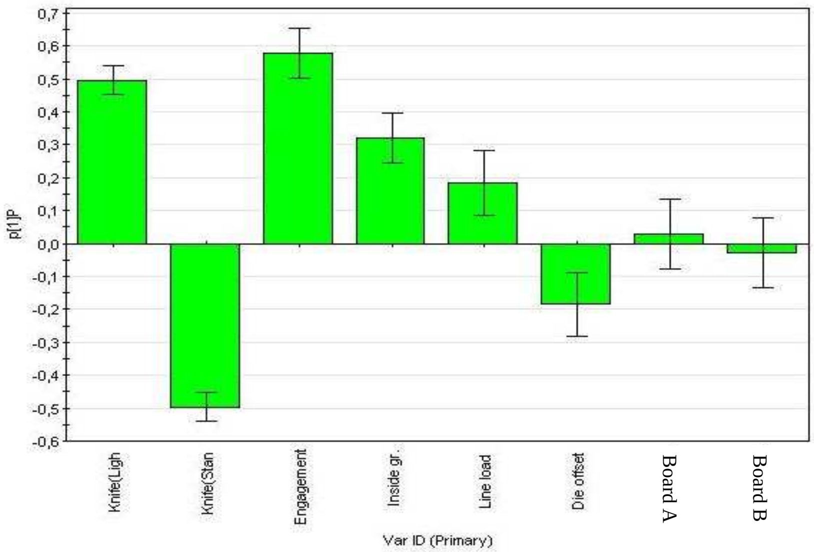


Figure 74 - First component for total energy response

The ability to predict values of Total energy by using the model is not very good. As goodness of prediction was only just above 0.5 the predicted versus the actual values shows more of a scatter than a linear relationship following the regression line as seen in Figure 75.

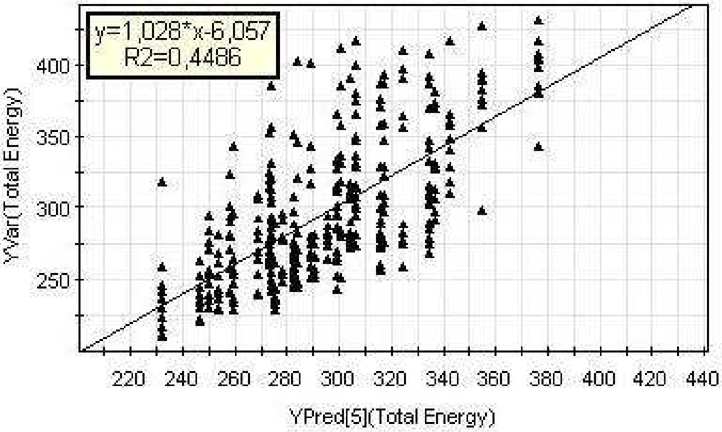


Figure 75 - Actual value vs. predicted value

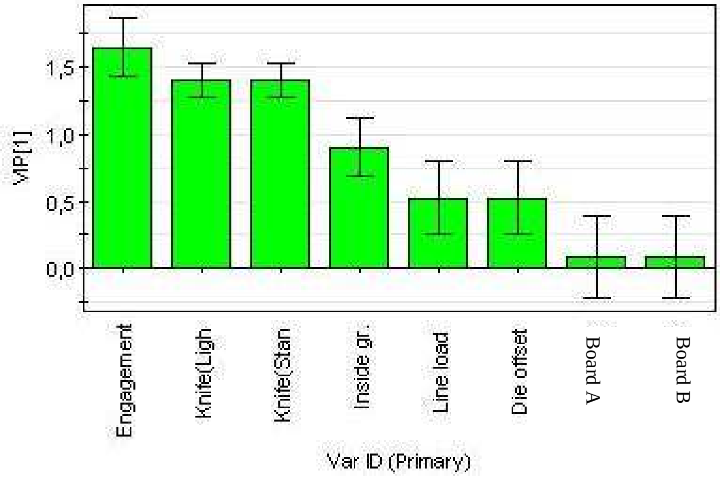


Figure 76 -VIP Total energy

In the variable importance plot in Figure 76 one can see which variables being most important to model the total energy response. The result does not surprise very much and the perforation of the board is most important when measuring Total energy. Looking at the Energy/cell response the result is very similar but with a higher importance of knife type and a bit better ability to predict. It can be found in *Appendix D.*

As the openability sum can be seen as the actual value of package performance regarding opening it is interesting to see how this value is affected by the input parameters as well as if it is possible to correlate the measured responses from mechanical tearing with this result. In Figure 77 and Figure 78 it is possible to see how openability sum and measured responses relate to each other and see that the total energy is the most important factor with the smallest variation with 95% confidence interval.

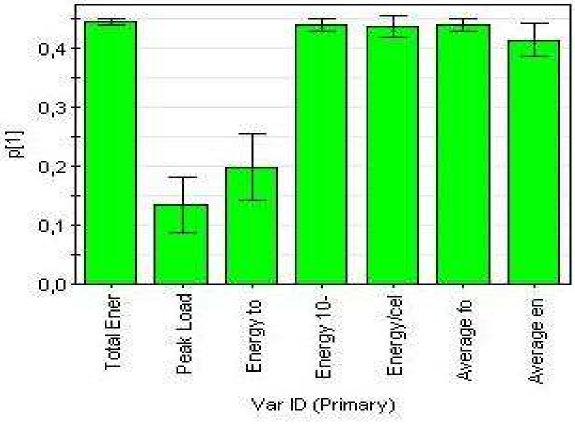


Figure 77 – First component Openability sum response

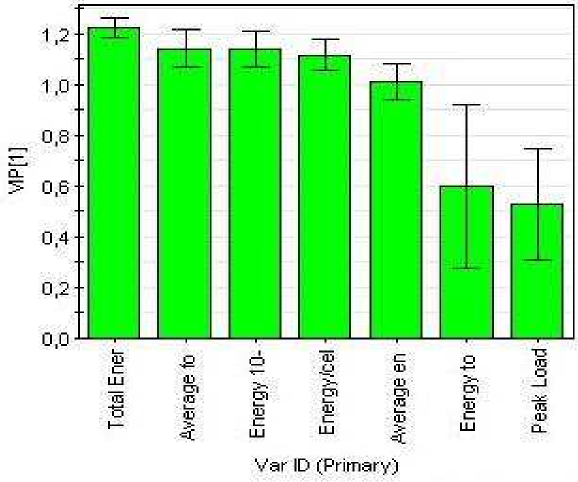


Figure 78 - VIP openability sum measured responses

If one instead uses the input values as X variables in the model and the openability sum as Y variable there are also interesting results seen in Figure 79 and Figure 80. Comparing it with the response of Total energy seen in Figure 74 on page 75 one can see that the engagement has less importance, knife type still describes a lot of the model and that inside grammage now is the most important variable to describe the openability sum model. Interesting to see is also that the two different boards change their influence and the board A that increases the Total energy decreases the openability sum. One should keep in mind that the data analyzed includes much more values from board A which probably affect the result.

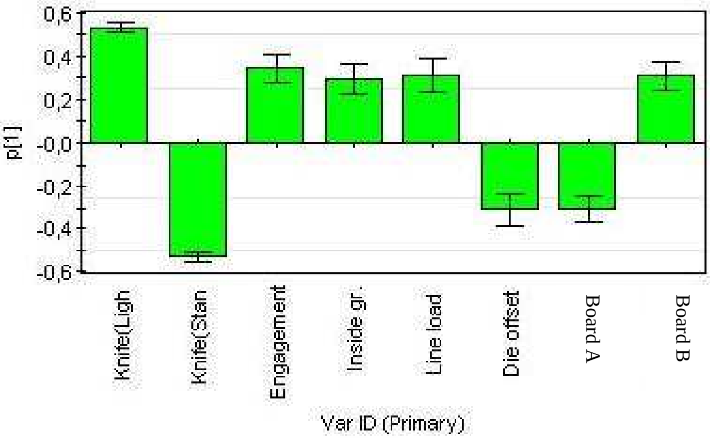


Figure 79 - Comp 1 of openability sum regarding input values

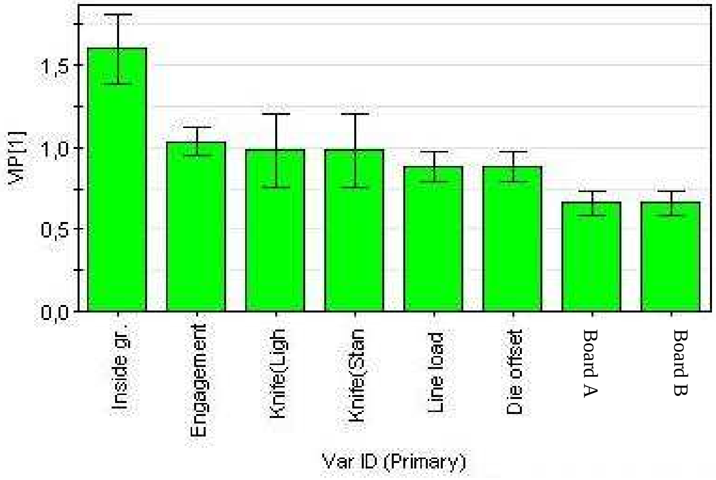


Figure 80 - VIP of op. sum regarding input values

6.3 Quantitative test analysis

When looking at the results presented in *6.2.2 Tearing Energy Absorption test result* one can see that the Total energy is the best measurement to distinguish between material specifications and perforation engagements. The Peak load did not explain any of the material differences and as the measurements of energy after the peak and average force did not increase our knowledge the Total energy is seen as the most reliable and robust measurement response. As the factorial experiment showed the Total energy is affected the most by PE-strength and Adhesion. To keep in mind regarding this measurement is that the engagements used as high and low level was web 3 and 4 which we can not separate by the Total energy according to Figure 66 on page 68. If one instead looks at the SIMCA analysis it shows that perforation strength has a major impact on Total energy by changing knife type and engagement. The Total energy difference can be seen in Figure 66 and the affecting parameters in Figure 74 on page 75.

In Figure 81 one can see how the Total energy is affected by the Line load pressure as well as the inside grammage. Higher grammage of the polymer and higher line load pressure increase the energy to tear by mechanical tearing. As the Die offset is changed parallel to the Line load pressure one can not say which of those parameters that affect the total energy according to Figure 81. The SIMCA analysis supports these results seen in Figure 74 and it is clear that the combination of high Line load pressure and low Die offset, which should create lower adhesion, decreased the tearing energy and openability sum. Even if not the measured adhesion is affected by this process parameters according to Table 10 on page 71 it is clear that it has an impact on both tearing energy and openability.

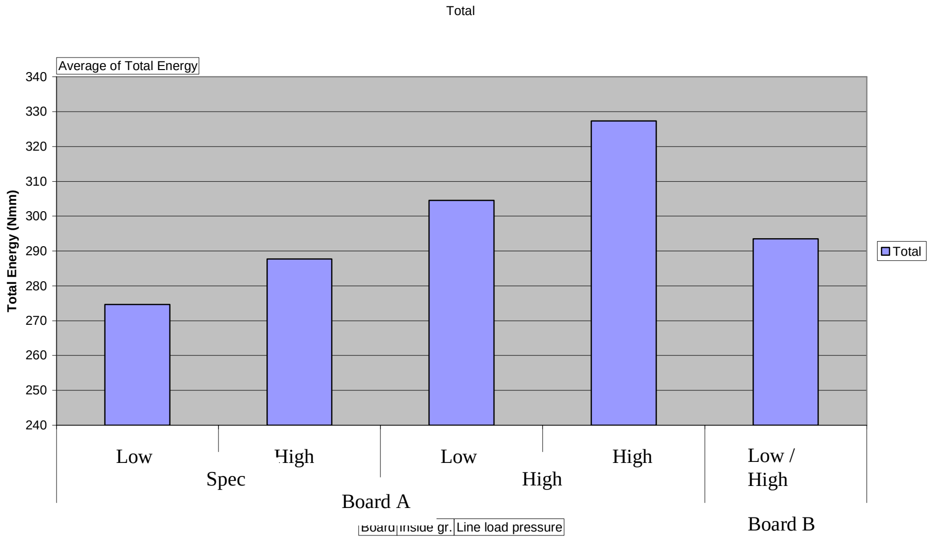


Figure 81 - Total Energy with changing PE-strength and Line Load pressure

One has showed that it is possible to see differences between our 35 samples by measuring total energy and it increase the need of also finding a link between Total energy and Openability sum. As our openability measurements, achieved by opening packages, can be seen as the end consumer’s ability to open packages, this link has to be established. Not until then can the Total energy tell us how engagements and polymer weights affect the end user. Unfortunately only 19 of 35 variants have been opened which affect the result. Looking at the same picture as in Figure 81, but regarding openability instead of Total energy, one can see a different relationship.

Figure 82 show how the A board with high inside grammage and low line load pressure scores worst in openability in contrast with the total energy.

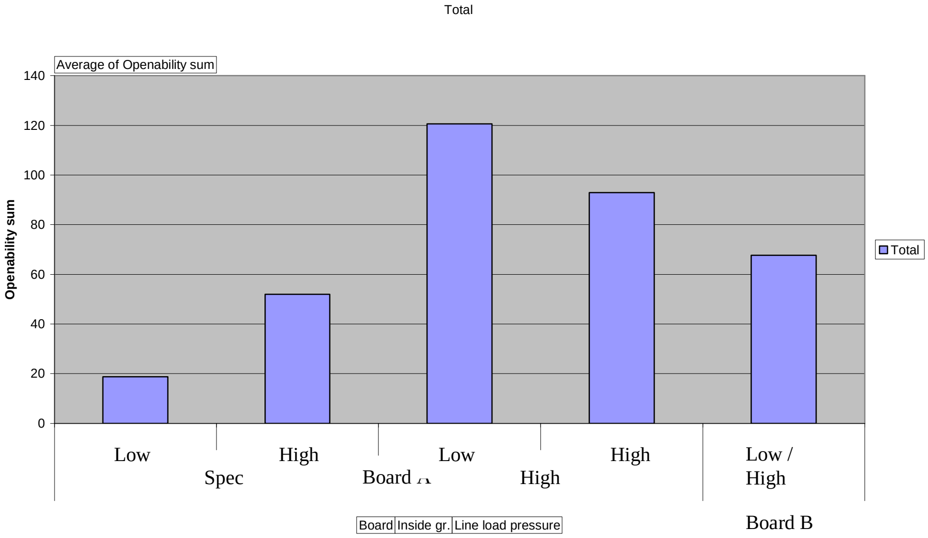


Figure 82 - Openability sum with changing Line load pressure and PE-strength

In earlier tests prior this work, most of the focus has been put into the Peak load and in *5.4.1 Energy peak* it is shown that this measurement is influenced by set-up factors that are hard to control. To once again see if there is any relationship between Total energy, Peak load, and Openability sum scatter plots are made.

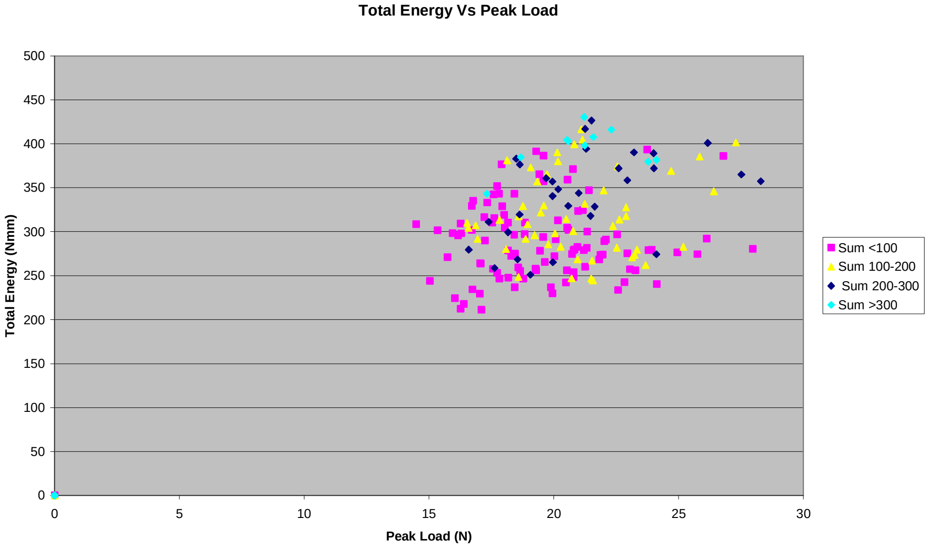


Figure 83 - Total Energy vs. Peak Load

In Figure 83 there are four categories of openability based on the Openability sum, one color each, and one can not see any significant grouping but only tendencies between the measured values and the openability. The tendency of the average values, which can also be seen in *Appendix E*, is that higher total energy gives worse openability but there is nothing similar within Peak load. Similar plots are made for other measured values and one can see how Total Energy and e.g. Energy 10-20 mm follow each other by looking at Figure 84.

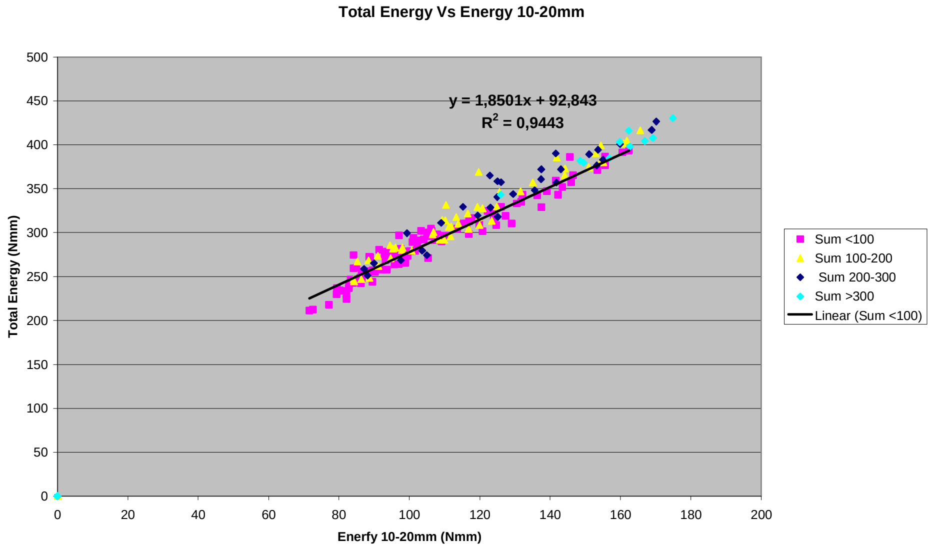


Figure 84 - Total energy vs Energy 10-20mm

The R&R result was not satisfactory at all but it did anyhow increase our knowledge about the process. As the R&R value is very sensitive to the R-values it is not hard to understand that up to 50% in internal variation is not good enough. But if one looks at the X-bar chart it is still possible to distinguish between the different samples. If this can be done the method can still be used to classify material by using control charts with upper and lower control limits. In this case it does not matter if two values that should be the same differ as long as both are inside or outside the control limits. Of course the bad R&R value and high internal variation can question the validity of the results but this is often the case in destructive tests when no sample is similar to the other. Looking at the results in Figure 85 one can see that there in most cases are higher standard deviations for higher Total energy values. Operators and the two similar knifes per revolution do not have the significant difference as one can see between the four different materials.

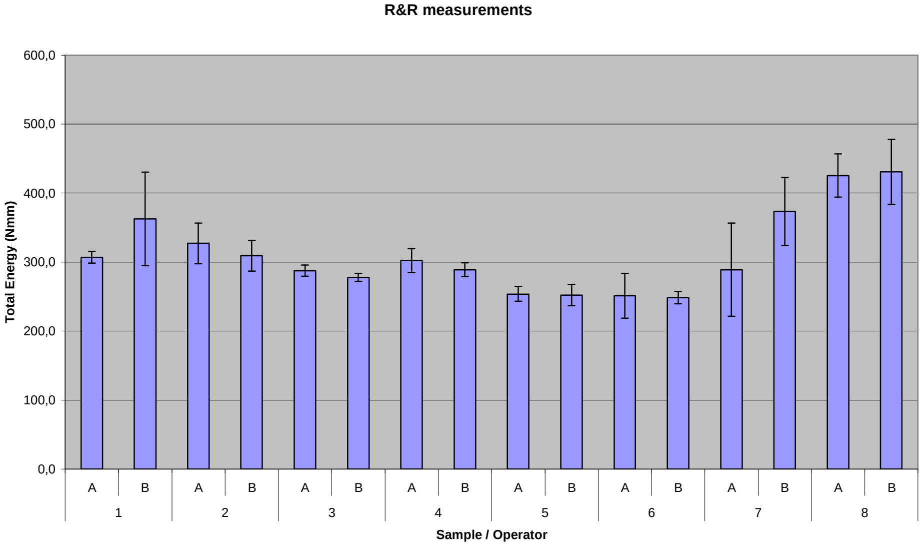


Figure 85 - R&R measurements

When looking at the multivariate analysis done with SIMCA software one could have hoped for better result. The validity of the models and their ability to predict was in best cases just above 0.5 which is acceptable but not more. Something to have in mind is that this does not mean that the mechanical tearing method is bad but that the results used is not good enough to build a model on. But when looking at the models, keeping in mind that they explain about 50% of reality, they overlap with earlier results and conclusions. It is good to know that the models confirm earlier tests instead of rejecting them. For the energy measurements it is the knife engagement and knife type that matters the most. Polymer strength is also a factor that rise the tearing energy when it is increased. Focusing on the openability sum instead, the total energy response has the most impact on the result and is also the response with least variation with 95% confidence interval. When one looks at how the input variables affects the openability sum the knife type and engagement still are very important but according to Figure 80 on page 78 the polymer strength is the most important variable in the model.

6.4 Summary Quantitative tests

The aim of this part of the thesis was to analyze a lot of measurements with a quantitative approach. This has been done in many different ways which can be seen as waste of time and a risk of achieving contradicting results. But in this case, when results are overlapping, one can be more convinced about that they are true. The Total energy is the response that describes the process most accurately and even if the other energies measured also work, they are less robust and have a higher internal variation. As the Peak load is used for now in

an opening force method it has been important to highlight its performance tested by both SIMCA and R&R.
When it comes to form a correlation between openability and Total energy it is not crystal clear. One can see that higher Total energy increase the risk of bad openability but there are not enough measurements to decide what levels of Total energy that is acceptable. Looking at the two last analyses, SIMCA and R&R, there are much more to hope for. As the R&R shows how inadequate the measurement gauge is this has to be kept in mind when looking at results. The sometimes poor SIMCA model probably has its root in the used data and it can probably be improved by using Design of Experiments when deciding the input parameters and their levels. If one goes back to Figure 4 on page 9 and the relationship mentioned, one would likes to specify it more closely and find out where in the 3-dimentional space one should be during converting to minimize openability problems. In Figure 86 “Adhesion” is changed to Lamination process due to the lack of relation between chosen parameter settings and adhesion measurements. Within the volume in the picture there should be fewer problems with openability. The most important thing to show is how one can achieve a wider process window for one parameter by setting the others at the right level. One still does not know the root cause of openability issues to fully understand the process and decide optimal factors for each variable but so far one can summarize it as follows:

PE-strength: The higher grammage of polymer used the harder it will be to avoid PE-residues.

Perforation strength: Current perforation process specification, not allowing partial cut, is suitable. One should try to use standard knifes if the integrity allows it and one shall not neglect differences between board types.

Lamination process: One still does not know how to address this issue. This time the tests showed results contradicting previous test results.

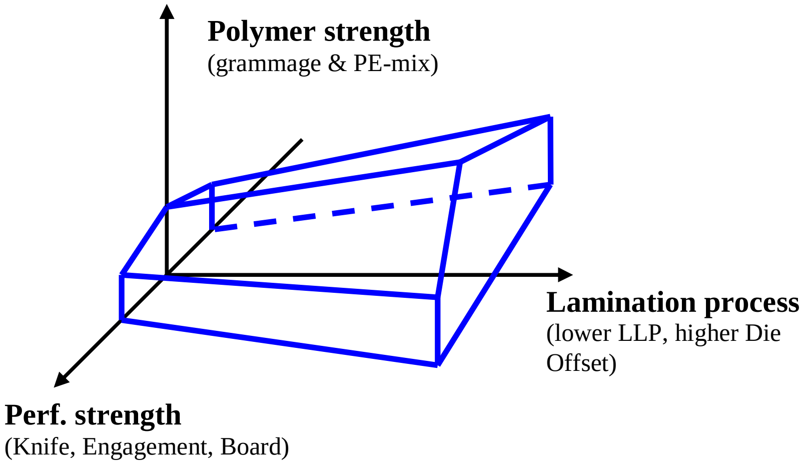


Figure 86 - Parameter relationship

7 Conclusions

In this chapter one can find the conclusions drawn from all the tests and what new knowledge that is achieved by this work.

- By using the mechanical tearing process one achieves a modus III tear opening. Tear force is 10 times lower than tensile force due to shear forces and out of plane breakage.

- When trying to predict openability regarding polymer residues on final packages the total energy during tearing is the most effective measurement to use.

- A method based on measuring tearing energy will be able to distinguish the worst performing material and process combinations.

- To continue with mechanical tearing the process needs to be improved to make sure the results are more reliable. A lower R&R value should be achieved by changing the process and not by choosing more suitable material. As it is a destructive test one does not think an index far below 30% is achievable but to lower the internal variation will be enough to be able to use the data with confidence.

- The process and part-to-part variations are too big to be able to find differences among materials produced within the specifications.

- One does not have enough data, covering the whole process window, to fully correlate Total energy response with openability performance. So far one can only separate the very good and very bad samples.

8 Further work

Further work is where the author has the possibility to recommend Tetra Pak how to continue this work and what issues to address to improve further investigations regarding this tearing method and the openability problem.

- Investigate if tearing energy measured by mechanical tearing is the test method for perforations that one should continue to work with. Will an improved version be useable to test perforations either in factory or in package material quality laboratory? If not, it can probably be used internally when new material specifications and perforation designs are evaluated.

- Revise the Opening Force method and make decisions of which clamp, speed, tearing length etc that should be used in the future. Base these decisions on tests with the purpose to minimize the internal sample to sample variation and measure Total energy instead of Peak load. Make sure that the same settings are used by everyone using the method.

- Find the root cause of the openability problem. Is it the converting process or the filling machine that has the largest impact on performance? If filling machine has a low impact one should continue to measure tearing energy on packaging material.

- If one continues with this method next big test should be based on Design of Experiments and a better SIMCA model will be achieved.

- Considering growing need for quality measurements for thin materials it would be interesting to identify problems and find solutions to overcome existing issues with these measurements.

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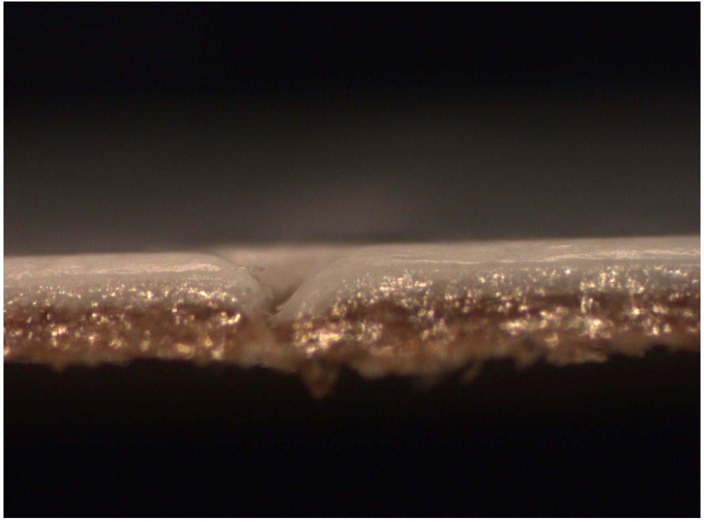
10 Appendix

Appendix A

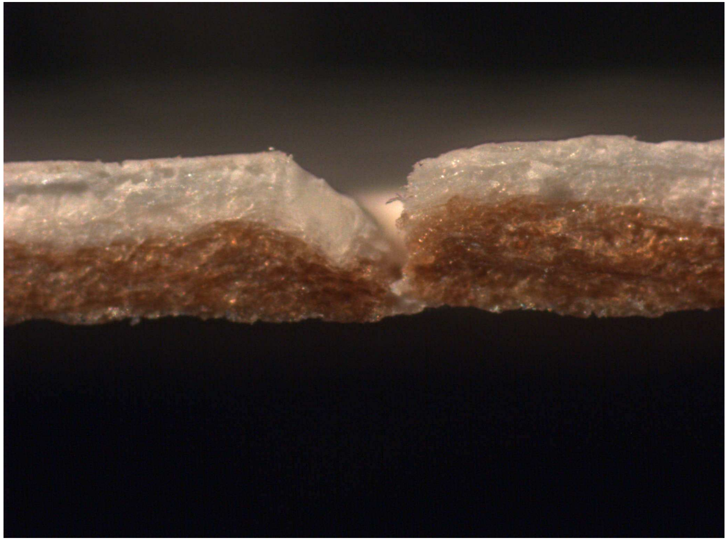
Appendix A contains some microscope pictures of perforation cuts from board A. It is two from each web, Web2-Web5. One that shows the cross section of the perforation and one that shows the bottom side of the board showing how much one has gone through the hole.

Web 2 / -0,02 mm

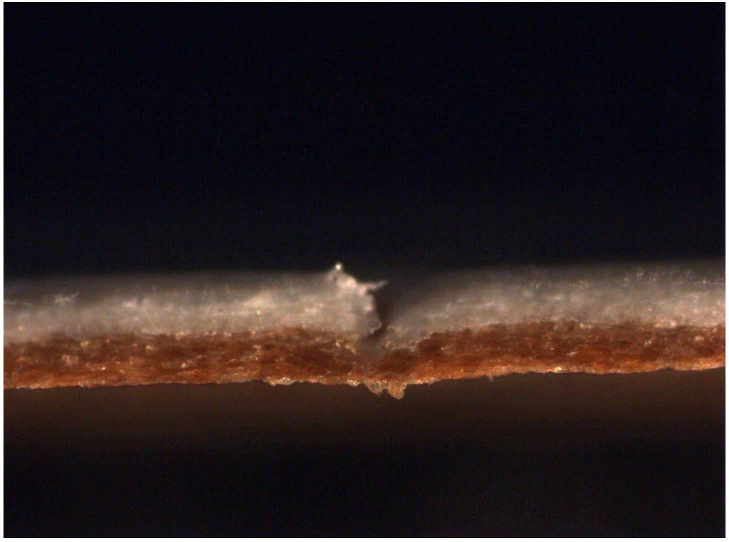


Web3 / -0,06mm

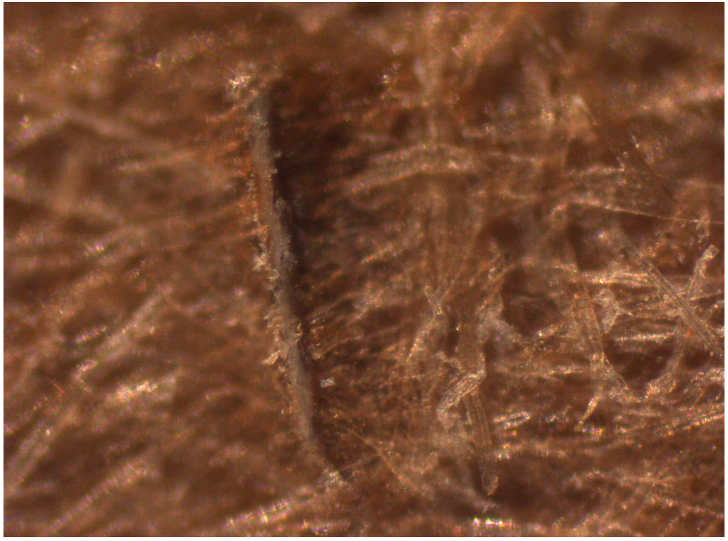
Web 4 / ± 0,00mm



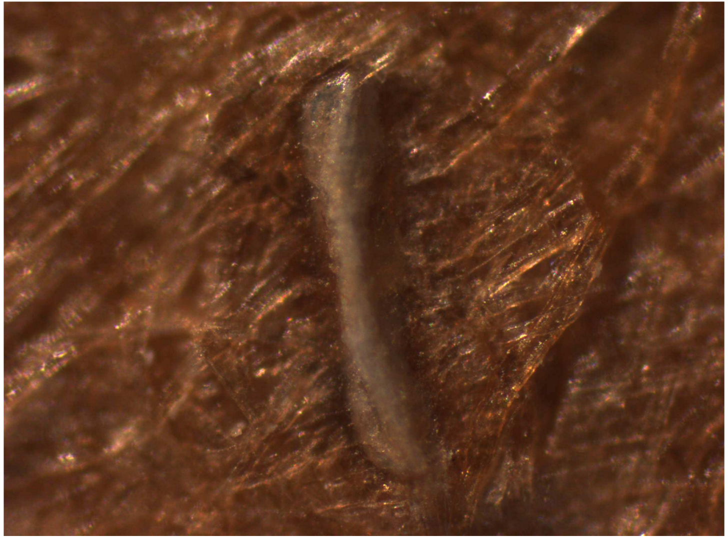
Web5 / +0,08mm



Web2 / -0,02mm

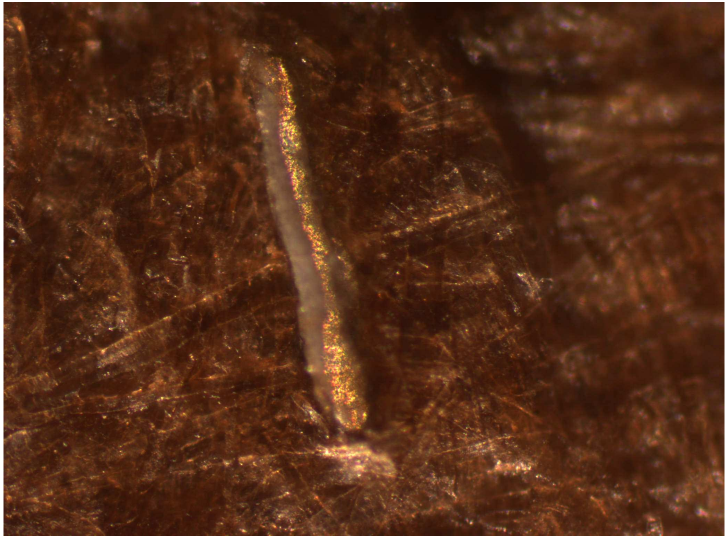


Web3 / -0,06mm

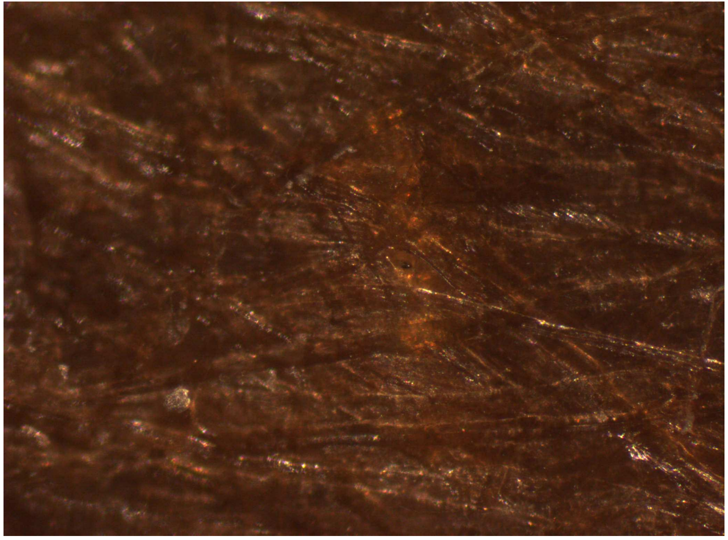


Following pictures are from the inside of the board lighten from underneath to show how much light that comes through.

Web4 / ±0,00mm



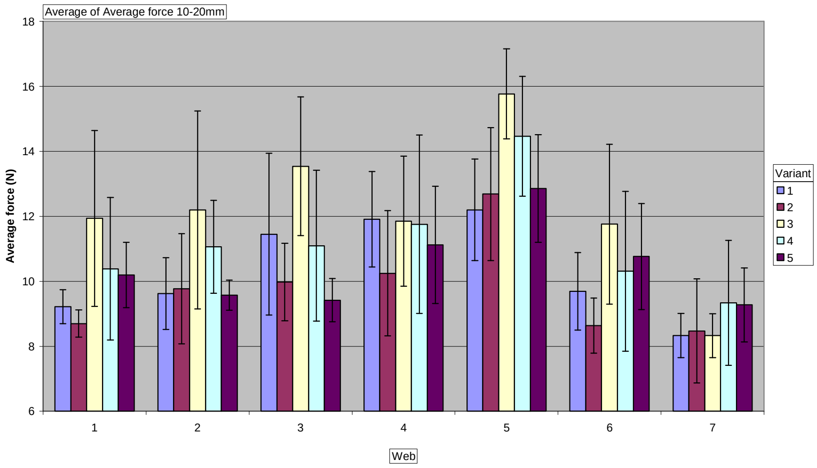
Web5 / +0,08mm



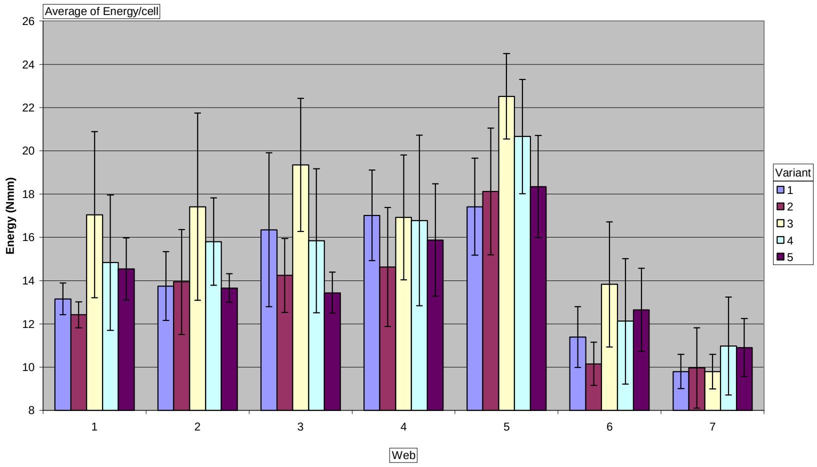
Appendix B

Appendix B shows the same charts as in Figure 66 on page 68 but for average force and Energy/cell responses instead.

Average force



Energy/cell



Appendix C

Appendix C shows the R&R calculations from the Total energy, Peak load and Energy/cell responses. The R&R values are in bold in the right column. It is unknown why the Reproducibility has a value for Peak load response as it should be zero.

R&R Total Energy

		Study Var	% Study Var
Source	**StdDev(SD)**	**6*SD**	**%SV**
Total gage R&R	33,6843	202,106	**47,69**
Repeatability	33,6843	202,106	47,69
Reproducibility	0	0	0
Part-to-Part	62,0812	372,487	87,90
Total Variation	70,6308	423,785	100,00

R&R Peak Load

		Study Var	% Study Var
Source	**StdDev(SD)**	**6*SD**	**%SV**
Total gage R&R	3,41508	20,4905	**74,76**
Repeatability	3,10067	18,6040	67,88
Reproducibility	1,43131	8,5879	31,33
Part-to-Part	3,03404	18,2042	66,42
Total Variation	4,56817	27,4090	100,00

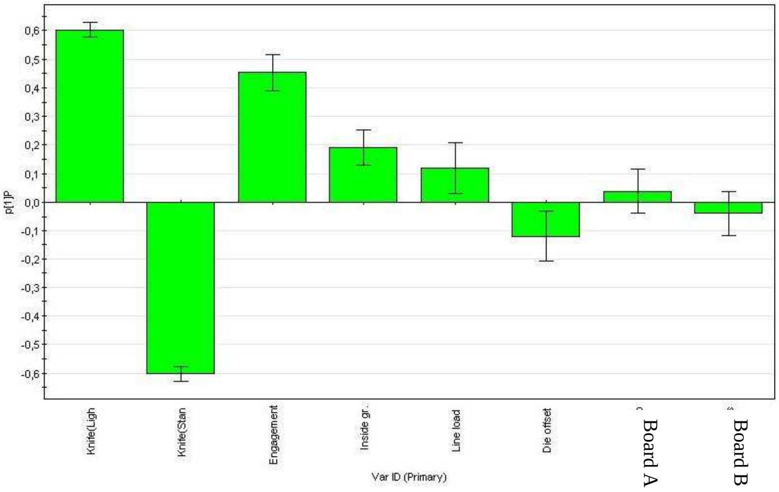
R&R Energy /Cell

		Study Var	% Study Var
Source	**StdDev(SD)**	**6*SD**	**%SV**
Total gage R&R	2,58440	15,5064	**49,01**
Repeatability	2,58440	15,5064	49,01
Reproducibility	0	0	0
Part-to-Part	4,59688	27,5813	87,17
Total Variation	5,27356	31,6414	100,00

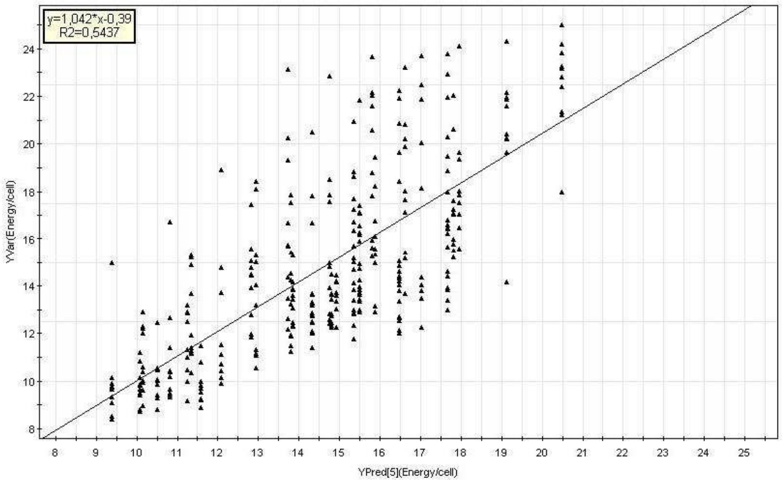
Appendix D

In appendix D one can see the describing plots from the Energy/cell response.

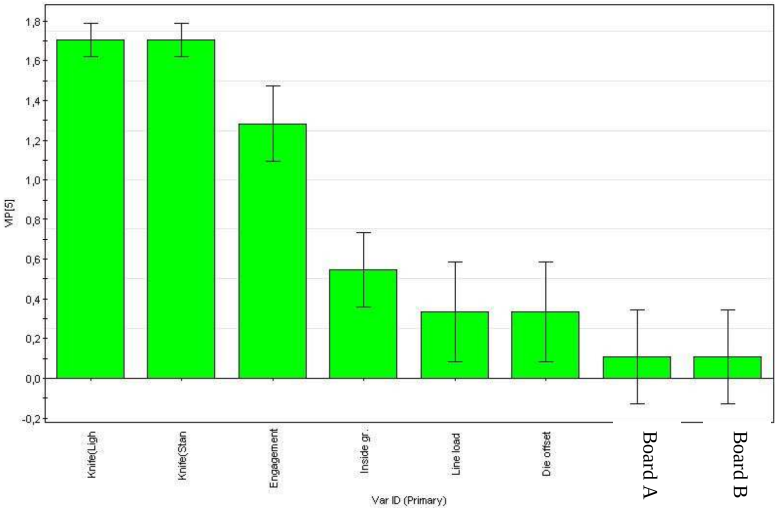
First component plot of Energy/cell



Observed v. predicted

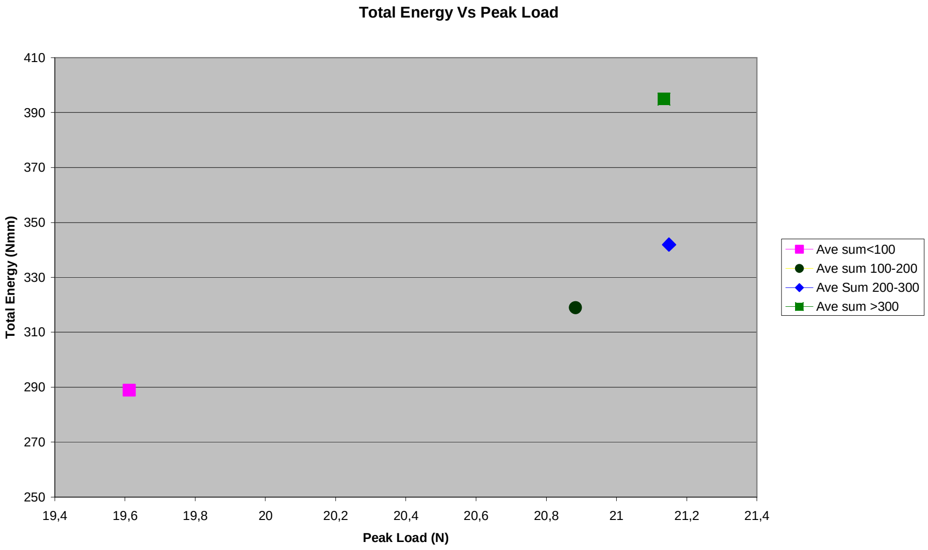


VIP for Energy/cell

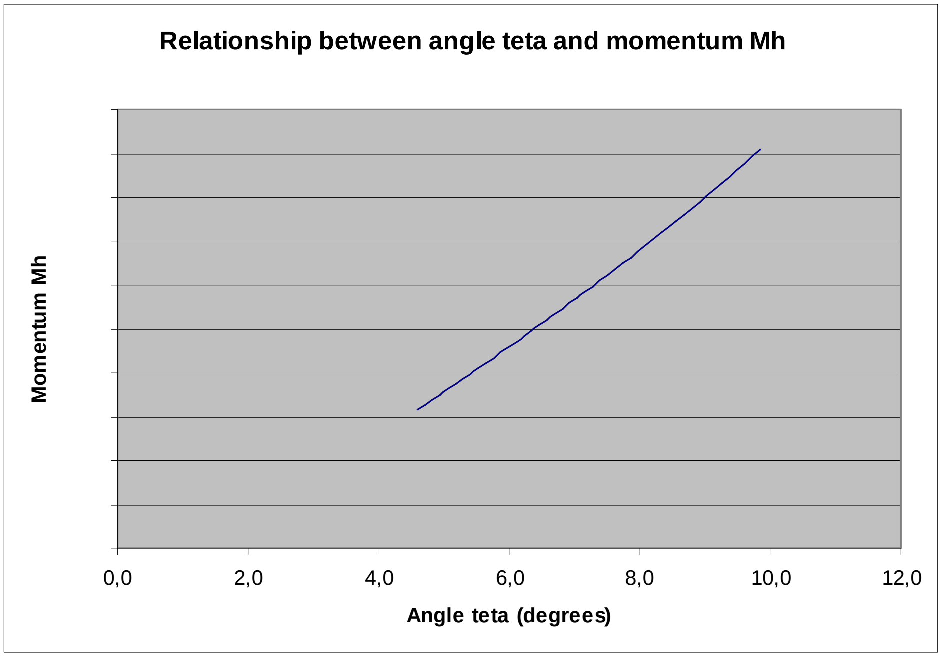


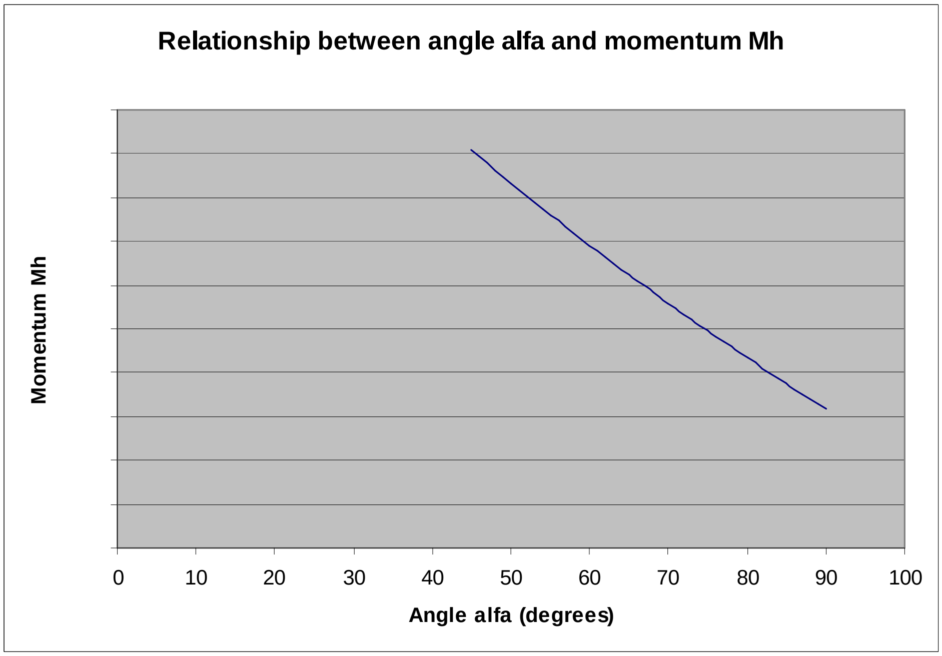
Appendix E

These are the average calculations of Total Energy and Peak load for each group of openability sum in the scatter plot in Figure 83 on page 80.



Appendix F


Relationship between angle teta and momentum Mh
Momentum Mh
0,0
2,0
4,0
6,0
8,0
10,0
12,0
Angle teta (degrees)


Relationship between angle alfa and momentum Mh
Momentum Mh
0
10
20
30
40
50
60
70
80
90
100
Angle alfa (degrees)