Fracture Behaviour of adhesive Joints in carton board
Fracture Behaviour of adhesive Joints in carton board
Licentiate Thesis, October 2007

Fracture Behaviour of Adhesive Joints in Carton Board

Christer Korin
Abstract

A carton-board package is often sealed and closed with an adhesive. Package requirements vary depending on how the package is to be used. A package that is only supposed to protect the product during transport differs from one that is supposed to attract consumers and facilitate the use of the product by consumers. Fracture of the adhesive joint may occur in several different ways, e.g. cohesive fracture in the adhesive, interfacial fracture between the adhesive and one of the carton-board surfaces, and cohesive fracture in the carton board. The traditional way of testing the adhesive joint is to subjectively evaluate the fibre tear after manually tearing the joint apart. The adhesives used in carton-board packages are either hot-melt adhesives (adhesives that are applied in a molten state on the carton board) or dispersion adhesives (adhesives that are applied as water-based dispersions).

The primary interest of this study has been to find an objective method that can characterise the adhesive joint, i.e. the strength and joint characteristics. The work has principally concentrated on physical experiments where the Y-peel method is evaluated and further developed, including construction of a laboratory adhesive applicator.

Adhesive joint failure is analysed and correlated to the force-elongation curve in order to explore various mechanisms of adhesive-joint failure. The force versus elongation curves are transformed into a force versus inelastic deformation curve for the adhesive joint. The inelastic deformation of the adhesive joint is defined as the inelastic opening of the adhesive joint perpendicular to the carton-board surface. The dissipative descending energy has been used to evaluate the adhesive joint. High descending dissipative energy resulted in high resistance against final failure of the joint. This correlates very well with the manual fibre-tear test. Characteristic force-elongation curves in Y-peel testing, i.e. the shape of the curve, have been analysed and found to have four main failure modes.

Using both the newly designed adhesive applicator and the Y-peel test method revealed a large discrepancy, about three orders of magnitude, between the theoretical thermodynamic analysis and the experimental test result. The new objective method can be used to design the interaction between the adhesive and the carton-board surface for a specific application. This can be achieved by modifying the carton board, the adhesive or the process parameters.
Papers included in the thesis


## Table of contents

Table of contents

1. Introduction ........................................................................................................................ 5
   1.1 Carton board ................................................................................................................. 6
       1.1.1 Transport and consumer packages ........................................................................ 7
   1.2 Sealing .......................................................................................................................... 7
       1.2.1 Sled sealing ............................................................................................................ 8
       1.2.2 Closure sealing ...................................................................................................... 8
       1.2.3 Adhesives .............................................................................................................. 8
       1.2.4 Adhesive-application process ................................................................................ 8
   1.3 Demands on the joint .................................................................................................... 9
       1.3.1 Problem ............................................................................................................... 10
       1.3.2 Research .............................................................................................................. 10

2. Method ............................................................................................................................. 10
   2.1 Adhesive applicator .................................................................................................... 11
   2.2 Y-peel ......................................................................................................................... 12
       2.2.1 Force elongation .................................................................................................. 13
       2.2.2 Interpretation and failure characterisation ........................................................... 14

3. Theories ............................................................................................................................ 15
   3.1 Fracture, wetting and adhesion ................................................................................... 15
   4. Results and discussion .................................................................................................... 18
   4.1 Typical failure modes ................................................................................................. 19
   4.2 Characterisation of failure modes ............................................................................... 20
   4.3 Y-peel characterisation and fibre tear ........................................................................ 21

5. Discussion ........................................................................................................................ 22
   5.1 Y-peel test method ..................................................................................................... 22
   5.2 Y-peel characterisation ............................................................................................. 22
   5.3 Y-peel failure ............................................................................................................. 23
   5.4 Demands on a joint ..................................................................................................... 24

6. Conclusions ....................................................................................................................... 24

7. Acknowledgements ......................................................................................................... 25

8. Reference .......................................................................................................................... 26

9. Notations .......................................................................................................................... 28
1. Introduction

People have always made packages and receptacles in which to protect their goods during storage and transport. When people first started collecting and transporting materials, packages were made of natural materials suited to the contents of the package [1]. Examples of packaging from this period are earthenware jars, wooden cases, leather cases or even leaves. As technology and marketing concepts developed, the demand for more complex and sophisticated packages to meet transport demands, storage conditions and display provisions emerged on the market. At the dawn of the industrial era, mechanical converting machines expanded the possibilities for optimising package functionalities and creating new designs of modern packages. Today almost every product is packed in some sort of package during its entire product life or part of it. The products that are packed today are very diversified, e.g. ball bearings, batteries, toys, food, liquids, medicine and luxury products; e.g. cosmetics, liquor each of these products has its own requirements on the package. The package material is also much more varied, e.g. paper, glass, metal and plastic.

The traditional role of the package was to protect the product for the consumer during storage and transport. An additional important and increasing demand today from consumers and the industry is to make the package an integrated part of marketing. Thus, the initial function of the package evolved from not only protecting the product during transport and storage but also to informing and displaying data on it, as well as providing the consumer with a positive overall experience of the contained product [2], from when the product is sold until when it is used and disposed of. When the consumer decides to pick and buy a product off the shelf, the package has a large influence as a “silent salesman” [3]. The package/product on the shelf that catches attention and looks good is chosen. This is called “the first moment of truth”. “The second moment of truth” [2] is when the consumer decides to buy the product a second time, and this depends on the relation between the consumers’ expectations and experiences when using or consuming the product. The combination of the package and its product thus creates the total experience of the product.

The process of producing a packaged product from carton-board reels includes several converting steps such as printing, embossing, creasing, cutting, punching, folding, gluing, erecting, filling and sealing. This can be done in one single in-line converting process or in several discrete stand-alone machines that cover one or more converting steps. Each converting step is a scientific and technical challenge in itself.

Packages can be sealed several different ways, such as by gluing, stapling or mechanical interlocking. This thesis will focus on the process of gluing, material properties, and process conditions affecting the performance of the adhesive joint. The mechanical strength of adhesive joints in carton-board packages is an important product property of the package so that the sealed package meets the demands on it throughout its complete life cycle. A reduced operating window caused by increasing production speed and automation leads to an increased demand for an objective method for testing the mechanical strength of adhesive joints. How to optimise package sealing for a specific package application becomes more and more important because a failure in the converting process causes more losses in productivity when increasing speed in the production process. Using the wrong adhesive can turn out be too expensive with respect to either customer problems or reduced profit for the producer. The joint has to fulfil expectations throughout the complete life cycle of the package from converting, distribution, consumer and recycling perspectives. It is important to have an objective and quantitative joint testing method as a tool for gaining more knowledge about the
quality of adhesive joints in carton-board packages and for optimising the cost-performance relations in the entire value chain.

1.1 Carton board
Carton board is usually defined as a paper material ranging from about 200 g/m² up to 600 g/m². If the grammage is less than 200 g/m², the material is usually called paper; if it is higher than 600 g/m², millboard. Carton board is often made as multiply board (sandwich construction). With this type of multiply board, the producer has the possibility to design the properties of each ply to meet various demands for different applications. Carton board is an anisotropic material with different properties in the in-plane directions – the machine direction (MD), which is the direction in which the board is produced on the board machine, and the cross-machine direction (CD) – and the out-of-plane direction – the thickness direction (ZD). The in-plane stiffness properties are 100 times or more higher than the out-of-plane stiffness; see Table 1 [4]. Furthermore, the in-plane tensile yield stress is at least ten times higher than the failure stress in the out-of-plane direction.

Table 1. Experimental results of uniaxial tensile tests in the MD and CD and of through-thickness tensile tests in the ZD of a multiply board [5].

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>MD</td>
<td>5600</td>
<td>12</td>
<td>44</td>
</tr>
<tr>
<td>CD</td>
<td>2000</td>
<td>6.5</td>
<td>18</td>
</tr>
<tr>
<td>ZD</td>
<td>18</td>
<td>-</td>
<td>0.40</td>
</tr>
</tbody>
</table>

The carton board used in this thesis is a four-ply carton board from Korsnäs Frövi. The carton board is built up from the bottom ply with unbleached softwood sulphate pulp, and in the two middle plies, there is a mixture of unbleached softwood sulphate pulp, unbleached softwood chemi-thermo-mechanical pulp (CTMP), and internally produced broke from the board machine. The top ply is a mixture of softwood and hardwood bleached sulphate pulp, and on top of that, there is a pigment-coated surface.

Figure 1. The Korsnäs Frövi carton board LIGHT 330 in cross section, both schematically and as a SEM micrograph.
1.1.1 Transport and consumer packages

Package requirements vary depending on how the package is to be used. A package that is only supposed to protect the product during transport differs from one that is supposed to attract customers and facilitate the use of the product by consumers.

The board and the transport package must withstand the stresses – such as folding, stacking, water/moisture and vibration – that it will be exposed to during converting, filling/loading and transportation. Smaller consumer packages can be packed in a transport package for distribution from the manufacturer to the supermarket or shop. The size of the transport package is then adapted to contain the number of consumer packages that is convenient for the shop or supermarket to handle. The different sizes and applications define the specific demands on the sealing until the package is opened. In addition, the transport package may also be used as a display package, i.e. a package that urges the consumer to buy the product from the shelf in the shop, which adds further demands on the sealing. In this case, it is important that the sealing opens as desired.

The consumer package must withstand the stresses that the material and the package are exposed to during the complete lifecycle of the package, from converting the blanks to erecting, filling, transportation, shelf exposure, consumption of the content to the final recycling of the package and/or the material. Hence it follows that the production and transportation demands placed on the adhesive joint, the package must also live up to the expectations of the consumer to reinforce the total product experience [2]. From the consumer’s point of view, the transport package will be useless immediately after opening (e.g. a transport box for a refrigerator), whereas the consumer package may be used for a longer period of time (e.g. packages for breakfast cereals, butter, fruit juices or cosmetics).

The demands on adhesive joints differ depending on whether the package is a transport package, consumer package or combined transport/consumer package. It is not desirable that first-time opening destroys the appearance or function of the package if the package is elaborately decorated and if it will be used by consumers over a long period or if it will be used as a display package on a store shelf. In such cases, fracture involving tearing or delaminating is not desired. On the other hand, maximum toughness may be preferred irrespective of the fracture process for packages where the entire content will be used at once. In some cases, it is desirable that the adhesive joint opens with a distinct snap-like manner. This requires low toughness but high strength in order for the package to resist converting and withstand transportation to the consumer.

1.2 Sealing

Fracture of the adhesive joint may occur in several different ways, e.g. cohesive fracture in the adhesive, interfacial fracture between the adhesive and one of the carton-board surfaces, and cohesive fracture in the carton board. Most of this bonding is due to chemical interactions across the interface such as Lifshitz-van der Waal and acid-base interactions (cf. [6]). In addition, diffusion and entanglement of polymer molecules between the substrate and the adhesive may increase the adhesion; mechanical interlocking between the adhesive and the substrate may also have the same effect.
1.2.1 Slid sealing
Here slid sealing is defined as all kinds of sealing that occur before filling. These sealings are generally not opened when the content is being used. Therefore it is important that this type of joint is intact and closed during the complete package chain. The demand on this type of joint is to resist the stresses and not to fail. If the joint eventually fails, then the character of the failure is normally of no interest.

1.2.2 Closure sealing
The closure sealing, here defined as the closure of a filled carton-board package, is sometimes easy to open with a short click sound, and in other cases, it is tamper-proof. When a package is nicely decorated and is to be used over an extended period of time, then it is desirable that the first-time opening of the seal is easy and does not damage the appearance of the package through fibre tear. On the other hand, when a tamper-proof seal is required, then the opening of the seal must result in significant fibre tear as an obvious sign or evidence that someone has opened or tried to open the package.

1.2.3 Adhesives
The adhesives used in carton-board packages are either hot-melt adhesives (adhesives that are applied in a molten state on the carton board) or dispersion adhesives (adhesives that are applied as water-based dispersions).

A typical traditional hot-melt adhesive has these main chemical components:
- 30–40% polymer
- 20–30% wax
- 30–40% resin

The polymer gives the adhesive its cohesive mechanical strength; i.e. it is the glue substance. The resin is the wetting substance, whereas the wax gives the viscosity and regulates the adhesion (i.e. the tack) when the adhesive is applied on the carton board. Normally, a small amount of antioxidants are also added, and they protect the adhesive from ageing [7].

Hot-melt adhesives often have a chemical basis of ethyl vinyl acetate or polyolefin, and are designed to suit the carton-board packaging industry. No dispersion adhesives have been used in this study.

1.2.4 Adhesive-application process
In the machine converting process of producing carton-board packages, there are different ways of sealing, e.g. stapling, adhesive sealing, adhesive tape and mechanical interlocking. With increasing machine speed, the use of adhesive seals has increased as well. Adhesives also make it easier to produce nicely designed packages with high-quality printed decorations and different, untraditional shapes. At the same time, it is important for the industry that the converting process runs with very few interruptions and that it has a high and constant quality because of the fierce competition on the market.
It is important to be able to control the application of the adhesive, i.e. application of the
adhesive on the substrate, wetting of the board by the adhesive, consolidation of the adhesive,
and the final joint formation to control the quality of adhesive joints (the adhesive joint is in
this context defined as two sheets of carton board with a hot-melt adhesive in between). This
control is possible by controlling certain process parameters. The most important parameters
to get the full and intended strength of the joint are:

- open time
- pressure time
- pressure on applied adhesive string
- amount of applied adhesive
- temperature of applied adhesive

To withstand certain package conditions, it is important that the adhesive is applied in such a
manner as to avoid indications of fracture.

1.3 Demands on the joint

In the beginning, the demands on a package were that it was able to be closed and that the
content was protected. The appearance of the seal was of practically no importance. In
some cases, however, it was important that the seal was tamper-proof. Later during
industrialisation and in machine production, runability was added as an important factor. It
was important for profitability that the machines run fast, smoothly and with few stops. The
optimisation of package sealing for specific package applications became more and more
important because a jam in the converting machine would cause a large drop in productivity.
In addition, poor sealing can be very expensive with respect to customer complaints and loss
of image on the market. The joint has to resist the demands throughout the complete life cycle
of the package.

To optimise the adhesive joint, it is not only necessary to know whether the adhesive joint is
good or bad but also how good or bad. The contribution from mechanical bonding can be
particularly important for carton board where the mechanical bonding is achieved through
mechanical interlocking of the adhesive into irregularities and pores of the carton-board
surface and the embedding of fibres sticking out from the surface (see [9], [10]), and creates
fibre tear. In other cases, pop-up behaviour is required where a low degree of fibre tear is
needed. To enable measurements of adhesive joints in an objective manner, it is appropriate to
use a tensile test machine and measure the force-elongation curve.
1.3.1 Problem
The demands on the adhesive joints originate from loading and environmental conditions (e.g. forces from the surroundings such as other packages, dynamical forces from the machines, and/or climate changes such as temperature and relative humidity) during converting, transport, storage, exposure on shelf, end use of the product and finally recycling. Fracture of the adhesive joint may occur in mainly three different ways:

- cohesive fracture in the adhesive
- interfacial fracture between the adhesive and the carton board
- cohesive fracture in the carton board

Fibre tear

No fibre tear

Figure 3. Two Y-peel specimens torn apart, with and without fibre tear.

The failure may also be a combination of the above-listed failure modes. Several different test methods exist [11] such as the T-peel, angle-peel and Y-peel methods.

The first step is to find a procedure to make adhesive joints in a repeatable way in order to investigate how the adhesive joint behaves when different specified parameters are changed. Enhanced wetting will lead to higher work of adhesion (see [12]). The traditional way to test a joint is to conduct a manual peel test [4] and subjectively evaluate the degree of fibre tear. To control the converting process, an objective method has been developed; this method includes a laboratory adhesive applicator and a test procedure that tears apart the adhesive joint in a well-defined manner.

1.3.2 Research
The purpose with this work is to find an objective test method to characterise how good or bad an adhesive joint is when exposed to mechanical loading. In addition, the test method should be repeatable and correlate with practical experience in the converting industry. This study of adhesive joints is mainly done through physical experiments where the Y-peel method is evaluated and further developed for the characterisation of the mechanical strength of adhesive joints in carton-board packages. The adhesive-joint failure is also analysed and correlated to the force-elongation curve to explore various mechanisms of adhesive-joint failure. The force-elongation curves are analysed with the expectation to gain knowledge about the behaviour of the adhesive joint during crack propagation and to make it possible to predict the behaviour of the adhesive joint during stress.

2. Method
The traditional way of analysing the mechanical strength of a hot-melt adhesive joint in the converting industry is to look at the fracture surfaces after manual peeling. The joint is
acceptable if there are more than 50% fibres on the fractured adhesive surface; otherwise, it is considered bad. However, this method is very subjective and based on personal skills and experience. There are other semi-manual peeling methods in which the joint is subjected to a load, either an increasing load until the joint fails or a constant load, and the time to failure is measured [13]. Other methods are based on using tensile testing equipment in which the force-elongation curve is recorded during peeling until the joint fails.

Figure 4. T-peel, angle-peel and Y-peel [11].

Peel tests suggested in the literature for carton board-based packaging materials are, e.g., the T-peel tests [13], Figure 4 (left); the angle-peel tests [14], Figure 4 (middle); and the Y-peel tests [11], Figure 4 (right). These methods all have their advantages and disadvantages. In the T-peel test method, the adhesive joint is not fixed relative to the tail and the tail is free to move during the test. Ways to overcome this movement are to stabilise the tail by holding the tail in a fixed position or by adding a stabilising tab [13], [15].

In the angle-peel and the Y-peel test methods, no arbitrary movement is allowed. It is further observed that in the angle-peel test, the sample needs to be bonded to a sliding support block. This makes the preparation work for the angle-peel test more time consuming compared to the other two methods. The Y-peel method is a redesign of the constrained T-peel test. The Y-peel method is discussed in detail below.

2.1 Adhesive applicator

In this study, a laboratory adhesive applicator was designed in co-operation with IM-Teknik. A prototype was built, Figure 5, and today fully developed equipment is commercially available from IM-Teknik, Gothenburg, Sweden. The process by which the adhesive glues two board surfaces together involves a number of steps [4], and the adhesive applicator is required to be able to simulate the different process parameters in the adhesive line of a converting and filling machine.

It is possible to set these different process parameters in the developed adhesive applicator:

- open time – the time from application of the adhesive on one board surface until the other sheet is pressed against the adhesive string
- pressure time – the time during which the adhesive joint is set under pressure
- pressure on the joint – the pressure that is applied on the adhesive joint in the adhesive applicator
- amount of adhesive – the amount of adhesive that is applied on the sheet
- **temperature** – the temperatures in the adhesive aggregate tank, hose and nozzle
- **application speed**

![Image of adhesive applicator components](image)

Figure 5. Photo of the adhesive applicator, with its various components labelled.

### 2.2 Y-peel

To produce repeatable test results, the Y-peel equipment was redesigned and adapted to the Y-peel samples. Sample preparation for the Y-peel test method is fully described by Tryding et al. [4]. The Y-peel fixture is set up into the uniaxial tensile tester (Figure 6). During a test, the uniaxial tester pulls the upper clamp with a constant speed and continuously records the resulting forces with corresponding prescribed deformations. As the upper clamp moves, the Y-peel specimen stretches, which ultimately leads to a fracture in the adhesive joint of the Y-peel specimen. The Y-peel specimen is mounted in hinged upper and lower clamps so that movement will be free of friction. The free ends cannot move uncontrolled because they are fixed in the clamps.

![Image of Y-peel fixture](image)

Figure 6. Photo of the fixture with the mounted Y-peel specimen.
Figure 7. The Y-peel set-up together with a sketch of the geometry and boundary conditions. \( \Delta \) is the displacement of the point of fracture opening during testing.

The set-up of the Y-peel method is shown in Figure 7 together with sketches of the geometry and boundary conditions. In the middle of Figure 7, the load \( P \) is acting on the upper simply supported clamp of the set-up. The resulting reaction forces \( R \) at the two simply supported clamps at the lower part of the set-up are of the same magnitude. The forces are all aligned parallel to the specimen legs. Force equilibrium gives the relation

\[
P - 2R \cos(\alpha/2) = 0
\]

where \( \alpha \) is the peel angle; see the middle of Figure 7. Using the symmetry line in the Y-peel set-up gives the reaction forces and moment at the adhesion joint zone; see the right of Figure 7. The reaction forces in vertical and horizontal direction are denoted \( F_v \) and \( F_n \), respectively. The moment is denoted as \( M \). In this set-up, \( \Delta \) is considered small enough to justify the approximation of \( M \approx 0 \). Force equilibrium in the vertical and horizontal planes then gives, using eq. (1), the relation

\[
F_v = 0 \quad \text{and} \quad F_n = \frac{P}{2} \tan(\alpha/2)
\]

respectively. Note that the reaction force, \( F_n \), on the right of Figure 7, is perpendicular to the board surface (for detailed discussion see Korin et al. [11]).

2.2.1 Force elongation

The force-elongation curves have to be separated into their elastic and dissipative (inelastic opening) regions before they can be analysed in a relevant and objective way; see Figure 8 [11].
Figure 8. Typical total force-elongation curves from Y-peel tests and identification of the elastic component and extraction of the dissipative part [11].

Typical force-elongation curves for a test sample are shown in Figure 8. The area for extracting the remaining elastic energy is marked $W_{el}^{remain}$; the dissipative ascending and descending energy are marked $W_{D}^{asc}$ and $W_{D}^{desc}$ respectively [11]). The total elongation is denoted $u$, whereas the elastic part of $u$ is denoted $u_e$, and the dissipative part of $u$ is derived as the difference $u - u_e$. The initial energy caused by initial tightening of the specimen is called $W_{D}^{init}$.

The crack propagation begins and ends in the dissipative part of the force-elongation regime, and the fracture development depends on how the crack propagates after its initiation.

### 2.2.2 Interpretation and failure characterisation

It is possible to derive the inelastic behaviour of the adhesive joint by separating the recorded force-elongation curve into elastic and dissipative parts (Figure 8). The testing method is described in the publication [4] and the mathematical derivations in [11]. This is based on the fact that the proportional limiting yield strength in the in-plane direction is at least ten times higher than the out-of-plane failure stress [ref 5, 16]. Inelastic deformation is hence confined to out-of-plane deformation of the adhesive joint. Using the equations

$$F_s = \frac{F}{2}$$

and the inelastic opening $\delta^w_e = 2(u - u_e)$

[11], [17], the force versus elongation curve can be transformed into a force versus inelastic deformation curve for the adhesive joint (Figure 9). The inelastic deformation of the adhesive joint ($\delta^w_e$) is defined as the inelastic opening of the adhesive joint in the direction of $F_e$. 


3. Theories

The dissipative energy can be computed from the force versus inelastic deformation curve of the Y-peel test. The dissipative energy is caused by the formation of cracks, which in turn is due to the formation of microcracks and the subsequent coalescence of these cracks in the thickness direction of the carton board, or by inelastic deformation and damage of the adhesive. Hence, the dissipative energy is a measure of the amount of energy that is consumed during opening of the joint. As can be seen in Figure 9, the dissipative energy can be divided into an ascending and a descending part.

The force equilibrium means that the carton board and the tensile test machine will behave completely elastic, while the adhesive joint will fail out-of-plane (Table 1). The combination of the relative proportions and the magnitudes of the elastic, ascending dissipative work, and descending dissipative work [11] make it possible to objectively characterise how good or bad a certain adhesive joint is for a particular package application. The ascending part is the first part of the curve that ends at the maximum force ($F_{\text{max}}$), cf. Figure 9. The energy that is consumed during the ascending part of force versus inelastic deformation is denoted $W_{\text{asc}}$.

The descending part of the curve starts at the maximum force and ends where final failure occurs. During the descending part of force versus inelastic deformation, the coalescence of microcracks and fibres pulled out from the carton board result in a softening behaviour [5]. Part of the softening behaviour may also be due to the deformation and fracture in the adhesive as such. In some cases, however, a rapid failure occurs at the maximum force so that the descending dissipative energy is essentially zero. The energy that is consumed during the descending part of force versus inelastic deformation is denoted $W_{\text{desc}}$.

3.1 Fracture, wetting and adhesion

Fracture of the adhesive joint may occur in several different ways, such as:

- cohesive fracture in the adhesive
- interfacial fracture between the adhesive and one of the carton-board surfaces
- cohesive fracture in the carton board
The failure may also be a combination of the above-listed failure modes.

The work of cohesion \( w_c \), i.e. the surface energy per unit area associated with cohesive fracture in the adhesive, is equal to \( 2\gamma_c \), where \( \gamma_c \) is the surface tension of the adhesive. The work of cohesion in the carton board \( w_c \) could similarly be expressed as equal to \( 2\gamma_c \), where \( \gamma_c \) denotes the surface tension of the carton board.

The work of adhesion in the interface between the adhesive and the carton board is expressed by the Young-Dupré equation according to

\[
w_A = \gamma_a + \gamma_s - \gamma_{as}
\]

(4)

Assuming that the surface tensions of the carton board and the liquid adhesive in vacuum are approximately the same as the corresponding surface tensions in adhesive vapour (although adhesive vapour adsorption to some extent influences the surface tension of the substrate [18]), then the contact angle \( \theta \) could be derived from Young’s equation as

\[
\cos \theta = \frac{\gamma_a - \gamma_{as}}{\gamma_a}
\]

(5)

The contact angle is the angle between the upper surface of the liquid and the interface between the liquid and the substrate, when a small liquid drop is placed on a horizontal plane substrate. Hence, the contact angle \( \theta \) is a measure of wetting of the substrate by the liquid. Complete wetting results if \( \gamma_a - \gamma_{as} \geq \gamma_a \), leaving \( \theta = 0 \). This corresponds to the non-equilibrium situation when the liquid spreads infinitely on its substrate. The expression \( \gamma_a - \gamma_{as} \) corresponds to the empirical critical surface tension \( \gamma^* \) for the substrate [19]. Hence the substrate is completely wetted by the adhesive if \( \gamma_a \) for the substrate is greater than the surface tension of the liquid adhesive. By combining eqs. (4) and (5), the work of adhesion could be expressed as

\[
w_A = \gamma_a (1 + \cos \theta)
\]

(6)

From eq. (6), it is evident that enhanced wetting gives higher work of adhesion, a fact that has also been experimentally verified (see [12]). From eq. (6), it may seem as if the work of adhesion is always less than or equal to the work of cohesion of the liquid adhesive. Note, however, that for complete wetting \( \gamma_a - \gamma_{as} \geq \gamma_a \). As pointed out by [6], this implies that \( w_A > 2\gamma_a = w_c \) for complete wetting conditions. This suggests that fracture in such cases would occur as cohesive fracture in the adhesive, rather than interfacial fracture between the substrate and the adhesive. This may be true for ideally brittle conditions, but in most cases the bulk of the material (the adhesive and the carton board) experiences energy dissipation not only due to crack growth, but also due to inelastic deformation. To take such effects into account, deeper fracture mechanics must be considered.

Consider two solid sheets of carton board joined together with an adhesive. During the progressive creation of free surfaces (commonly referred to as crack growth), in the solid
board, the adhesive or the board-adhesive interface, energy balance for the body requires that (see [20])

$$\Delta \Omega = \Delta W + \Delta W_f + \Delta W_e$$  \hspace{1cm} (7)

where $\Delta \Omega$ denotes the energy put into the system by external forces, $\Delta W$ is the change in strain energy, $\Delta W_f$ is the total surface energy consumption during crack growth, and $\Delta W_e$ is the kinetic energy of the body during crack growth. The strain energy can be divided into its elastic and inelastic parts, $\Delta W_{el}$ and $\Delta W_{ie}$. The elastic energy is the part of the total strain energy that is recovered during unloading of the body. Eq. (7) can now be rewritten as

$$\Delta \Omega = \Delta W_{el} + \Delta W_{ie} + \Delta W_f + \Delta W_e$$  \hspace{1cm} (8)

The dissipative energy during crack growth is defined as $\Delta W_{ie} = \Delta W_{ie} + \Delta W_f$. Note that inelastic energy dissipation does not result in a change of elastic stiffness of the body as opposed to the energy dissipation associated with crack growth. In most cases, the strain energies vary as a function of position in the body, which means that $\Delta W_{el}$ and $\Delta W_{ie}$ are the integrated elastic and inelastic strain energy densities over the entire volume of the body. For non-homogeneous conditions, crack growth may occur simultaneously at different locations in a body meaning that

$$\Delta W_f = w_e \Delta A_e + w_i \Delta A_i + w_d \Delta A_d$$  \hspace{1cm} (9)

where $\Delta A_e$, $\Delta A_i$ and $\Delta A_d$, respectively are the incremental crack surface areas created in the adhesive, the solids, and the interface between the solids and the adhesive. The onset and progression of inelastic deformation and crack growth in a material is governed by the condition of forces at the point of the crack and the material’s ability to sustain those forces.

The work of adhesion according to eq. (4) represents the thermodynamic bonding between the adhesive and the carton board. High work of adhesion results if $\gamma_{as}$ is small, i.e. when the energy of the molecules at the interface approaches the situation in the bulk of a material. This requires strong bonding across the interface. Most of this bonding energy is due to interactions across the interface such as Lifshitz-van der Waal and acid-base interactions (cf. [6]). In addition to the thermodynamic bonding, diffusion and entanglement of polymer molecules into the substrate may increase the adhesion as well as pure mechanical bonding between the adhesive and the substrate. The latter contribution is particularly important for fibrous materials such as carton board where mechanical bonding is accomplished by the mechanical interlocking of the adhesive into irregularities in the carton-board surface and by the hooking of fibres sticking out from the carton-board surface (see [9], [10]).

If the total bonding across the interface is large enough, the adhesive joint may fail by cohesive fracture in the carton board or in the adhesive.

In polymer-based adhesives, such as hot-melt adhesives, the cohesive strength depends on the molecular structure of the polymer (see [21]). Micromechanically, cohesive fracture occurs by cavitation, fibrillation and crazing (see [22]). These processes involve a large portion of inelastic deformation. Carton board is known to have inelastic deformation when subjected to
loading in the thickness direction (cf. [23]). This means that cohesive fracture involves energy
dissipation not only due to crack growth, but also due to inelastic deformation. Therefore, the
thermodynamic work of cohesion (i.e. \( w_c \) or \( w'_c \)) is of less importance when predicting the
energy needed for cohesive fracture of the joint.

Cohesive fracture in multi-layer carton board either takes place deep in the board structure
between the plies of the carton board (see [24]) or in the outermost ply adjacent to the
adhesive and close to the surface of the carton board. The former type of fracture is often
referred to as delamination, while the latter is referred to as tearing of the carton board. Note
that the difference between interfacial fracture and cohesive fracture in the carton board (by
tearing) is not distinct.

Interfacial fracture with partial tearing is revealed by the observation that parts of the glue-
string area after fracture is covered by fibres. Complete tearing is when 100% of the glue
string is covered with fibres, and pure interfacial fracture is when no fibres at all stick to the
adhesive string. The expression “tearing” is normally used when more than 50% of the glue-string
area is covered by fibres after a fracture.

The interlaminar strength between the plies of a multi-layer carton board depends on how the
board is made, e.g. how the paper webs are dewatered and dried as well as whether starch is
added to improve the bonding between the board plies. The tearing strength and the bonding
strength of fibres to the surface of the carton board depend on the pulp composition, pulp
quality, added chemicals and a number of various process parameters. Many methods to
measure the behaviour and strength of carton board in the thickness direction exist, including
Z-toughness by [25] and Arcan by [23].

All in all, it appears that brittle failure is possible only if the joint fails by pure interfacial
fracture. The fact that no fibres are loosened from the carton board would then indicate that
the mechanical contribution to the interfacial strength is small in such cases. Maximum
toughness (i.e. dissipated energy) requires cohesive fracture, either in the carton board (by
delamination or by tearing) or in the adhesive.

4. Results and discussion
The newly designed adhesive applicator and the Y-peel test method have been used in
combination to test adhesively bonded carton board.
4.1 Typical failure modes
During the testing of 310 different samples, it was observed that the force-elongation curves could be grouped into four main types of failure mode, M1–M4, Figure 10.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Characteristics</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
<td>- single peak</td>
<td><img src="example1.png" alt="M1 Example" /></td>
</tr>
<tr>
<td></td>
<td>- sudden breakage at peak load</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- short displacement before breakage</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- no or very little recorded descending dissipative energy</td>
<td></td>
</tr>
<tr>
<td>M2</td>
<td>- single or multiple peaks</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- sudden breakage</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- relatively short displacement before breakage</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- small part of descending dissipative energy</td>
<td></td>
</tr>
<tr>
<td>M3</td>
<td>- single or multiple peaks</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- no breakage within target max displacement (3 mm)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- last part of force-elongation curve shows approximately constant force</td>
<td></td>
</tr>
<tr>
<td>M4</td>
<td>- single or multiple peaks</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- significant displacement before breakage</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- moderate slope after peak</td>
<td></td>
</tr>
</tbody>
</table>

Figure 10. Characteristic force-elongation curves in Y-peel testing with four main failure modes.

The modes in Figure 10 are categorised by the shape of the force-elongation curves. Mode M1 specifically has one single peak with an abrupt failure after a very short displacement with no or very little descending dissipative energy, a pop-up failure. Mode M2 still has a quick failure at a relatively short displacement, sometimes with several peaks, but it shows a small but measurable amount of dissipative descending energy. Mode M3, on the other hand, does not break completely within the specified maximum 3 mm displacement during testing. Several peaks are not uncommon, and it has a significant proportion of dissipative descending energy. The force is more or less constant during the final part of the force-elongation curve. Finally, mode M4 is similar to M3, with a significant proportion of dissipative descending
energy, but after one or several peaks, the force will gradually decrease during elongation until complete failure.

The majority of the 310 specimens had a mode M3 failure (Figure 11a). Mode M2 was the least frequent failure, and M1 and M4 were more or less equal.

Maximal force in the force-elongation curves showed no correlation with the failure modes except for failure mode M1 (Figure 11b), which appeared to have a generally lower peak force and a higher standard deviation.

Only failure modes M3 and M4 had a significant proportion of dissipative descending energy, $W_{D}^{dec}$ (Figure 11c). Failure mode M1 had in practice no $W_{D}^{dec}$ at all.

4.2 Characterisation of failure modes

The force and elongation curves were recorded during all the tests. In some tests, a digital microscope equipped with a video camera (TIMM 400 C, SPI GmbH, Oppenheim, Germany) was used to take pictures of the joint during testing. The picture sequences were automatically synchronised with the force-elongation curve (Figure 12). It was observed that the major crack was initiated through small cracks during the ascending part. The small cracks then merged during further elongation into a propagating major crack in the descending dissipative part, which finally led to failure.
Figure 12. Numbered photographs from the formation and propagation of a delamination fracture with corresponding positions in the Y-peel force-elongation curve numbered.

Characterised as fracture mode M3 with $F_{\text{max}} = 36.8$ N, $W_{D,W} = 45.4$ mJ.

In fracture mode M3 (Figure 12), the failure starts with small microcracks in the ascending part of the curve (pictures 2–4). The microcracks appear between the bottom ply and the first middle ply of the upper carton board in pictures 2–4. In the descending part, a major crack has developed (picture 5) at the lower carton board. This crack leads to final failure with fibres and the complete top ply being torn off from the lower carton board (picture 6). This is the carton board on which the hot melt was applied in the adhesive applicator.

In modes M1 and M2, which have an abrupt failure with very small crack resistance after crack initiation, the microcrack starts in the same way as in mode M3, but then the microcrack grows very rapidly to a major crack that causes the final failure with no visible fibre tear in mode M1 and some visible fibre tear in mode M2.

Mode M4 has a smooth curve, and the failure starts with the formation of microcracks in the ascending part. The microcracks then merge in the descending part of the curve to form the major crack leading to a final failure, where fibres abundantly have been torn off from either of the carton-board surfaces.

In this study, the major crack always appeared in the adhesive, in the board ply closest to the adhesive or at the interface between the outer and middle board ply. The failure never occurred in the middle board plies or at the interface between middle plies.

4.3 Y-peel characterisation and fibre tear

In a trial, the open time parameter in the adhesive applicator was changed over an interval to investigate the fracture process and how the crack propagated [11]. The idea was to test the traditional method with manual peeling and that subjective evaluation of fibre tear would correlate with a certain force-elongation curve or failure mode. The test showed that fibre tear
increases simultaneously with descending dissipative energy (Figure 13), until the strength of the adhesive joint exceeds the internal strength of the fibre structure in the outer ply of the board, leading to 100% fibre tear.

![Figure 13. Per cent of fibre-tear samples vs. descending dissipative energy. Dashed arrows indicate maximum internal strength of the outer plies of LGT and CRY.](image)

5. Discussion

5.1 Y-peel test method

A test method that objectively measures the mechanical properties in adhesively bonded carton board is the Y-peel method. To get good repeatability of the results, an adhesive applicator was developed for sample preparation of adhesive joints between two carton-board sheets. This laboratory adhesive applicator makes it possible to simulate the converting steps in a production machine and independently set the converting parameters: open time, press time, pressure on the joint, amount of adhesive, temperature, application speed and the choice of adhesive. After the sheets have been glued together, the laminate is cut in pieces that are suitable for the Y-peel test equipment, mounted and then torn apart in the uniaxial tensile tester, in which the force-elongation curve is recorded. Three parts of the force-elongation curve are identified: an elastic part, an ascending dissipative part and a descending dissipative part. These three parts are the basis for post-evaluation and characterisation of the force-elongation curve.

5.2 Y-peel characterisation

From the force-elongation graphs, it is possible to draw conclusions about when and how the crack propagates in the specimen.

- The maximum measured force gives information about when the major crack and the softening behaviour start.
- The dissipative descending part gives information about how the major crack propagates and how the failure behaves.
The ascending dissipative part has so far not shown any correlation fracture characteristics or crack propagation, probably because the microcracks start in the same way in all tested samples in this study.

In this study, a correlation between dissipative descending energy and fibre tear has been found. Therefore, the dissipative descending energy can be used as a practical assessment of the mechanical strength of an adhesive joint, a value that will reflect the experience of the general converter. The maximal force \( F_{\text{max}} \), on the other hand, will give information about when a crack in the joint is initiated, but it shows no obvious correlation with fibre tear.

The Y-peel method in combination with the adhesive applicator is an objective method to measure and characterise when fracture is initiated and how good or bad the joint is, which correlates well with practical experience (e.g. fibre tear).

### 5.3 Y-peel failure

Following the discussion in the introduction, it appears that brittle failure (i.e. fracture without inelastic energy dissipation) would be possible only if the joint fails by pure interfacial fracture. The fact that no fibres are loosened from the carton board would indicate that the mechanical contribution to the interfacial strength is small in such cases. To explore this matter, consider the brittle case of mode M2 with multiple peaks as in Figure 14. The fracture initiates as an interfacial pop-up failure reflected by the first two peaks of the force-elongation curve. Consider the second peak of the curve. From the video capture, the pop-up crack growth was estimated to be 0.3 mm, and the width of the specimen is 25 mm. The grey areas in Figure 14 represent the elastic energy released during the pop-up crack growth. This is estimated to \( \Delta W_e = -3.2 \, \text{mJ} \). Tests made with controlled displacement, as in the Y-peel test, lead to \( \Delta \Omega = 0 \) during fracture. The kinetic energy can be neglected because quasi-static conditions are restored after a small amount of crack growth. Combining eqs. (8) and (9) then gives

\[
\Delta W_e + \Delta W_p + w_c \Delta A_c + w_c \Delta A_c + w_c \Delta A_c = 0
\]

![Figure 14. The release of elastic energy during the pop-up crack growth.](image)

The inelastic part of the dissipated energy corresponds approximately to the light grey area in Figure 14. This estimate gives \( \Delta W_i = 0.65 \, \text{mJ} \). No crack growth is visible in the adhesive,
i.e. $\Delta A_a = 0$, and there is no visible crack growth taking place in the carton board during the pop-up fracture, implying $\Delta A_a = 0$. The surface created in the interface due to the pop-up crack growth is $\Delta A_{in} = 0.3 \cdot 25 = 7.5 \text{ mm}^2$. Inserting this into the above equation gives

$$\Delta W_{el} + \Delta W_a + w_A \Delta A_{ar} = 0$$

(11)

Solving $w_A$, based on experimental data, $w_A = 340 \text{ N/m}$.

Introducing Zisman’s empirical surface energy $\gamma_c$ into eq. (4) gives $w_A = \gamma_a + \gamma_c$. Assuming that the value for the surface energy of paperboard is $\gamma_c \approx 55 \text{ mN/m}$ [26] and for the cold consolidated hot-melt adhesive is $\gamma_a \approx 30 \text{ mN/m}$ [27] would result in that $w_A = 0.085 \text{ N/m}$. There is apparently a huge discrepancy between the surface energy derived from mechanical testing compared to the surface energy derived from thermodynamic calculations, even in cases behaving macroscopically “brittle”. This is in line with the conclusion by [12], who stated that enhanced wetting gives higher work of adhesion. Gent and Schultz simply introduced a magnification factor to cope with the fact that the experimentally measured work of adhesion was much higher than the calculated thermodynamic work.

5.4 Demands on a joint

The Y-peel test in combination with the developed adhesive applicator makes it possible to design the performance of an adhesive joint in carton-board packages or develop the carton-board surface to match the adhesive for specific applications.

If the demands on the adhesive joint are a small amount of dissipative energy and if the joint should open easily with little damage to the carton-board surface, then a seal with a force-elongation curve as in fracture mode M2 should be developed. This requires a combination of a relatively strong carton-board surface and a matching surface energy of the adhesive that permits the fracture to propagate at the interface between the board and the adhesive.

On the other hand, if it is important that the adhesive joint is tamper-proof but that relatively low force is needed to open it, then a seal with a force-elongation curve such as the one for fracture mode M3 should be developed. This in turn requires a relatively weak and porous board surface structure with a matching viscosity and surface energy of the adhesive during application to favour good wetting and mechanical interlocking of the board surface. This will force the crack to propagate into the board structure and damage the surface. Moderation of the force to open the joint can, in this case, be achieved by, for instance, changing the amount of adhesive applied or the temperature of the adhesive during application, shortening the opening time, or chemically modifying the adhesive itself.

6. Conclusions

The Y-peel method opens up a possibility for the converters to speak in relevant theoretical terms and define their demands on adhesive joints quantitatively. It will be possible to optimise the parameters for the converting process in terms of the combination of adhesive and carton board for specific package applications. It will also be possible to further develop
the adhesive and carton board to make them more compatible with the aim of obtaining an adhesive joint that works well throughout the entire packaging chain.

Future interesting research could be a finite element model of the Y-peel method to gain a better understanding of what happens and which properties have the biggest influence for the mechanical behaviour of an adhesive joint.

7. Acknowledgements

This work of research would not have been started or completed without the support and trust of my previous manager Johan Tryding at former AssiDomän Frövi. I really appreciate the interest he put in my work.

This work was made possible through the financial support from former AssiDomän Frövi, now Korsnäs Frövi, and Sveaskog. I am most grateful for this support. Thank you, Ola Karlsson (Korsnäs Frövi) for always believing in me and my work and for your support. Thank you also to Lars Ödberg (Sveaskog and KTH) for always having time for me and all my silly questions.

I would like to thank my project group and supervisors, who were there to encourage me and give me good advice and theoretical support as my work proceeded. To my supervisor Gunnar Engström (KAU) and vice supervisor Nils Hallbäck (KAU), with whom I co-wrote two papers, our workdays, which often included weekends, have been full of fun, encouragement and laughter. Vice supervisor Magnus Lestelius (KAU) has co-written two papers with me and is one of the persons who taught me the fundamentals of research. Johan Tryding (former AssiDomän Frövi, now TetraPak), also a coewriter of two papers, has been a great source of inspiration.

I also want to thank all the people who were involved in the technical development of the method and all the testing required for this research: Thomas Neumann, who drafted the design of the adhesive applicator; Johan Granat, who participated in the design and development of the adhesive applicator – it was always nice to talk with you; the support from Åke Eriksson when brainstorming new test methods, addressing computer questions and problems, and thinking about how the developed applicator could be further improved; Stefan Andreasson, who supported further development of the Y-peel method; Inga-Lill Jansson, who endlessly tested samples in the laboratory; and Roogher Johansson and Jonas Jarhäll for supplying adhesive and providing encouragement. I also had a great deal of help from Robert Junghans, Jakub Lewandowski, Therese Björklin and Anna Jansson with the preceding theoretical and practical work in the form of diploma work, trainee work and master thesis respectively, not to mention all my colleagues at Korsnäs Frövi who encouraged and supported me.

Torbjörn Widmark has helped me with the writing of the thesis, for which I am truly grateful. Thank you for your constant interest. Without your help, I do not know whether I would have finished this thesis.

My special gratitude goes to everyone in my family. My wonderful wife, Sofia, who was always there for me, supported and encouraged me when it was tough. My son, Evald, who never understood why Dad had to work so much with the computer.
8. Reference


17 C. Korin, N. Hallbäck and R. Junghans, Failure modes of adhesive joints in carton board, Submitted for publication (2007)


20 A. A. Griffith, The phenomena of rupture and flow in solids, Philosophical transactions of royal society, A221, 163-173 (1921)


9. Notations

<table>
<thead>
<tr>
<th>Notation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>MD</td>
<td>The machine direction, the direction in which the board is produced on the board machine</td>
</tr>
<tr>
<td>CD</td>
<td>The cross-machine direction, the direction in which the board is produced on the board machine</td>
</tr>
<tr>
<td>ZD</td>
<td>The out-of-plane direction, i.e. the thickness direction</td>
</tr>
<tr>
<td>CTMP</td>
<td>Chemi-thermo-mechanical pulp</td>
</tr>
<tr>
<td>P</td>
<td>The load acting on the upper simply supported clamp</td>
</tr>
<tr>
<td>R</td>
<td>The reaction force at the two simply supported clamps at the lower part of the set-up</td>
</tr>
<tr>
<td>( \alpha )</td>
<td>The peel angle</td>
</tr>
<tr>
<td>( F_i )</td>
<td>The reaction forces in vertical direction</td>
</tr>
<tr>
<td>( F_n )</td>
<td>The reaction force in horizontal, normal to the board surface</td>
</tr>
<tr>
<td>M</td>
<td>The moment</td>
</tr>
<tr>
<td>u</td>
<td>The total elongation</td>
</tr>
<tr>
<td>( u_e )</td>
<td>The elastic part of ( u )</td>
</tr>
<tr>
<td>( \delta_n )</td>
<td>The inelastic deformation of the adhesive joint; the inelastic opening of the adhesive joint in the direction of ( F_n )</td>
</tr>
<tr>
<td>( F_{n_{\text{max}}} )</td>
<td>The maximum force in the normal direction</td>
</tr>
<tr>
<td>( W^\text{remain}_e )</td>
<td>The remaining elastic energy</td>
</tr>
<tr>
<td>( W^\text{asc}_D )</td>
<td>The energy that is consumed during the ascending part of force versus inelastic deformation</td>
</tr>
<tr>
<td>( W^\text{desc}_D )</td>
<td>The energy that is consumed during the descending part of force versus inelastic deformation</td>
</tr>
<tr>
<td>( W^\text{initial}_D )</td>
<td>The initial energy caused by initial</td>
</tr>
<tr>
<td>( w_c^* )</td>
<td>The work of cohesion in the adhesive</td>
</tr>
<tr>
<td>Symbol</td>
<td>Description</td>
</tr>
<tr>
<td>--------</td>
<td>-------------</td>
</tr>
<tr>
<td>$\gamma_a$</td>
<td>The surface tension of the adhesive</td>
</tr>
<tr>
<td>$w'_c$</td>
<td>The work of cohesion in the carton board</td>
</tr>
<tr>
<td>$\gamma_s$</td>
<td>The surface tension of the carton board</td>
</tr>
<tr>
<td>$\gamma_{\text{irr}}$</td>
<td>The surface tension of the interface</td>
</tr>
<tr>
<td>$\theta$</td>
<td>The contact angle</td>
</tr>
<tr>
<td>$\gamma_e$</td>
<td>The empirical critical surface tension</td>
</tr>
<tr>
<td>$\Delta\Omega$</td>
<td>The energy put into the system by external forces</td>
</tr>
<tr>
<td>$\Delta W$</td>
<td>The change in strain energy</td>
</tr>
<tr>
<td>$\Delta W_f$</td>
<td>The total surface energy consumption during crack growth</td>
</tr>
<tr>
<td>$\Delta W_{el}$</td>
<td>The elastic part of the strain energy</td>
</tr>
<tr>
<td>$\Delta W_{in}$</td>
<td>The inelastic part of the strain energy</td>
</tr>
<tr>
<td>$\Delta A_a$</td>
<td>The incremental crack surface areas created in the adhesive</td>
</tr>
<tr>
<td>$\Delta A_s$</td>
<td>The incremental crack surface areas created in the solids</td>
</tr>
<tr>
<td>$\Delta A_{\text{irr}}$</td>
<td>The incremental crack surface areas created in the interface between the solids and the adhesive</td>
</tr>
<tr>
<td>$F_{\text{max}}$</td>
<td>The maximal force</td>
</tr>
</tbody>
</table>
Fracture Behaviour of adhesive Joints in carton board

A carton-board package is often sealed and closed with an adhesive. Package requirements vary depending on how the package is to be used. A package that is only supposed to protect the product during transport differs from one that is supposed to attract consumers and facilitate the use of the product by consumers. Fracture of the adhesive joint may occur in several different ways, e.g. cohesive fracture in the adhesive, interfacial fracture between the adhesive and one of the carton-board surfaces, and cohesive fracture in the carton board. The traditional way of testing the adhesive joint is to subjectively evaluate the fibre tear after manually tearing the joint apart. The adhesives used in carton-board packages are either hotmelt adhesives (adhesives that are applied in a molten state on the carton board) or dispersion adhesives (adhesives that are applied as water-based dispersions).

The primary interest of this study has been to find an objective method that can characterise the adhesive joint, i.e. the strength and joint characteristics. The work has principally concentrated on physical experiments where the Y-peel method is evaluated and further developed, including construction of a laboratory adhesive applicator.

Adhesive joint failure is analysed and correlated to the force-elongation curve in order to explore various mechanisms of adhesive-joint failure. The force versus elongation curves are transformed into a force versus inelastic deformation curve for the adhesive joint. The inelastic deformation of the adhesive joint is defined as the inelastic opening of the adhesive joint perpendicular to the carton-board surface. The dissipative descending energy has been used to evaluate the adhesive joint. High descending dissipative energy resulted in high resistance against final failure of the joint. This correlates very well with the manual fibre-tear test. Characteristic force-elongation curves in Y-peel testing, i.e. the shape of the curve, have been analysed and found to have four main failure modes.

Using both the newly designed adhesive applicator and the Y-peel test method revealed a large discrepancy, about three orders of magnitude, between the theoretical thermodynamic analysis and the experimental test result. The new objective method can be used to design the interaction between the adhesive and the carton-board surface for a specific application. This can be achieved by modifying the carton board, the adhesive or the process parameters.