Numerical analysis and experiments for increased understanding of cartonboard creasing and folding

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Abstract

Creasing and folding are vital processes in manufacturing of liquid and cartonboard packages. The quality of the crease and the subsequent folding is essential for good runnability and aesthetic appearance. The out-of-plane mechanical properties of cartonboard are particularly important in these processes. In this paper, recent advances in analysis of creasing and folding, using numerical simulations by means of the finite element method and the through-thickness shear strength profile of cartonboard, are presented.

Existing methods to determine the out-of-plane shear strength of paper materials only give the strength in the weakest layer. In order to capture the through-thickness variation in shear strength the laminated notched shear test was introduced.

In the simulations, the cartonboard was represented by a combination of continuum and cohesive models in order to capture the bulk and delamination properties, respectively. The continuum model was calibrated for each ply by testing individual plies that were isolated by grinding, and the cohesive model was calibrated using shear strength data from laminated notched shear tests.

Results from the simulations are compared with creasing and folding experiments and the agreement is excellent considering the relative simplicity of the analysis. Finally, practical implications for trouble-shooting creasing and folding problems will be discussed.

Introduction

Creasing and folding are important converting operations in manufacturing of cartonboard packages. During the creasing operation the cartonboard is locally damaged due to high shear stresses. The damage enables and enhances the foldability of the cartonboard. Most of the industrial knowledge on creasing and folding is empirical, and varies between different converters and board manufacturers. Thus, a deeper understanding of the deformation and
damage mechanisms in converting operations would be beneficial from a process optimisation and materials design point of view.

Cartonboard can, due to its fibrous structure and manufacturing on a commercial paper machine, to a good approximation be approximated as an orthotropic material with three principal directions (Figure 1): The machine direction (hereinafter referred to as MD or \( x \)), the cross machine direction (CD or \( y \)), and the out-of-plane or thickness direction (hereinafter referred to as ZD or \( z \)). Paper fibers are predominantly oriented in MD and the ZD:CD:MD stiffness ratio is typically 1:50:100.

Figure 1: Illustration of multiply cartonboard structure and coordinate system.

During folding the creased cartonboard is bent in order to form the corners of a package. Good folding quality is when the corner maintains its shape with little spring back and no cracks are formed in the outer plies of the cartonboard. This is achieved by creasing before folding so that local damage in the form of delaminations is introduced. This will enable the material on the inside of the corner to bulge inwards. The delamination cracks in the cartonboard open up and the bending stress in the outer plies is decreased so that cracks can be avoided. Based on this folding principle, the folding profile, which usually is explained by the relation between bending moment and folding angle, should reveal the bending peak value and softening due to the decreased bending resistance when the delaminated cartonboard open up. In previous folding analyses, Nagasawa et al. (2003) observe that when the crease depth is shallow the bending moment has a peak value, \( M_{\text{max}} \), and the peak value decreases by increasing the crease depth. The bending stiffness is also decreased with increasing crease depth. Besides, for shallow creases, \( M_{\text{max}} \) for MD folding (fold line parallel to CD) is larger than for CD folding. However, for deep creases, when the edge of the cartonboard is not constrained during creasing, the maximum bending moments for CD and MD folding are close. On the other hand, if the boundary of the cartonboard is fully
constrained during creasing, the maximum bending moments in MD and CD, respectively, for deep creases are different, but the difference is less distinct than after shallow creasing.

There are only few attempts in the literature that try to model the folding process. Carlsson et al. (1982) use a linear elastic fracture mechanics approach to evaluate the stresses in the creased zone during folding. Xia (2002) proposes a combination of elastic-plastic continuum and cohesive models to represent the cartonboard. Results from his folding simulations only capture the peak value and the bending angles predicted at the peak bending moment are larger than experimental values. Beex and Peerlings (2009) use a two dimensional elastic-plastic multiply continuum model and a cohesive zone delamination model, considering friction in contact, to simulate folding. Bex and Peerlings analyse four-point bending, and their results match the experimental results for bending angles up to 40 degrees.

Out-of-plane properties are the key factors for the mechanical behaviour of cartonboard materials, especially for converting operations such as creasing and folding. In the creasing operation, transverse shear is the dominating deformation and damage mechanism (Nygårds et al. 2009a). In many other operations, such as embossing, printing, package forming etc., a good design of the out-of-plane material properties also improves the performance.

Traditionally out-of-plane shear testing of cartonboard is performed by tests where the paper test pieces are glued between rigid blocks that are loaded to give a shear failure in the test piece (Byrd et al. 1975, Stenberg et al. 2001). However, such methods have limitations since the test, for example, is affected by glue penetration. To overcome some of these limitations, a double notch shear test method has been proposed by Nygårds et al. (2007). This test is based on a shear failure between two separated notches fabricated on opposite sides of a test piece loaded in tension. Thus, no gluing is needed. In order to avoid tensile failure, the specimen is strengthened by plastic foils that are gently laminated on the surfaces of the notched test piece. Using the laminated notched shear test (NST) a local measure of shear strength at a specific location in the thickness direction can be measured and a shear strength profile can be obtained by performing the measurements at different notch depths in the thickness direction (Nygårds et al. 2009b).

In this paper, it will be illustrated how a combined use of advanced simulations and a novel experimental technique can be used to gain more insight to the deformation and damage mechanisms of creasing and folding, and how this insight can be used in trouble shooting creasing and folding as well as in design of materials with improved converting properties. For this objective a two-dimensional finite element model for cartonboard creasing and folding introduced by Huang and Nygårds (2010, 2011) will be used in combination with the tilted laminated notched shear test (Nygårds et al. 2009b, Huang and Nygårds 2011).
Materials and Methods

All simulations and experiments were performed on a 0.65 mm thick commercial four-ply cartonboard. The elastic-plastic and cohesive properties of the cartonboard have been characterized by Nygårds (2008). The experiments were performed at a temperature of 23 °C and relative humidity of 50%.

Creasing and Folding Experiments

Creasing experiments were done in a simple laboratory creasing device that consists of a female die, a male ruler and two clamps as illustrated in Figure 2. The female die width was 2.1 mm, the depth was 3.0 mm, and the male ruler width was 0.7 mm. In the present analysis the clamps were located 40 mm from the creasing symmetry line. The clamps only prevented z-direction movement of the cartonboard, while they allowed movements in the xy-plane. The crease depth \( d \) was defined to be zero when the bottom of the male ruler was at the same position as the top surface of the female die. Hence, for a creasing depth \( d = 0.0 \) mm the male ruler was pushed through the whole cartonboard, and positive \( d \)-values indicate that the male ruler is below the top surface of the female die. Two crease depths were tested, \( d = 0.0 \) mm and \( d = 0.2 \) mm. The cartonboard test pieces had a width of 32 mm and a length of 80 mm. Creasing tests were performed in both MD and CD. After creasing, the cartonboard test pieces were folded.

The folding experiments were executed in an L&W creasability tester (AB Lorentzen & Wettre, Stockholm, Sweden). This apparatus is widely used for industrial converting quality control measurements. As shown in Figure 3, the cartonboard test piece is clamped on one side of the crease line by a rotation clamp and a load cell is located on the other side 10 mm
away from crease line. When the test machine is activated, the clamp will rotate 90 degrees. Meanwhile, the load cell records the reaction force produced by this rotation process.

Figure 3: Cartonboard folding experiments using the L&W creasability tester.

Tilted laminated notched shear test

Nygårds and Hui (2011) modified the notched shear test (NST) developed by Nygårds et al. (2009b) such that a shear strength profile can be acquired from one sheet. Test pieces were manufactured in four steps:

1. **Preparation of notches.** Two grooves with declining depth were grinded on each sheet on opposite sides and separated by a certain distance, the shear zone length $L$, using a 15 mm wide grinding wheel, as illustrated in Figure 4. The two grooves met at a certain position $z$ in the thickness direction, measured from the top surface. The value of $z$ along the sheet was estimated from measurements of the thicknesses using the STFI thickness meter (Schultz-Eklund et al. 1991).

2. **Lamination.** Two pre-cut 0.25 mm thick plastic foils (Perfex gloss 250 (175/75), GMP Co. Ltd. Lund, Sweden) were laminated onto each side of the cartonboard sheet in a laminator (Lamiart 320I).

3. **Cutting.** The laminated paper sheet was cut into strips of width $w = 15$ mm, as illustrated by the lines in Figure 5.

4. **Testing.** All the test pieces were tested separately using a tensile testing machine (Lorentzen & Wettre Alwetron TH1). In Figure 4 the red line represents a typical shear failure.
The test pieces were tested in the L&W tensile testing machine and failure occurred between the two notches.

The force $F$ was measured during the test, and the shear strength was calculated using the maximum force $F_{\text{max}}$ by assuming that the shear strain and stress field was uniform. This assumption is supported by numerical analysis in Nygård et al. (2009b). The shear strength $\tau$ was calculated from

$$\tau = \frac{F_{\text{max}}}{wL}.$$  \hspace{1cm} (0)

where $w$ is the width of test piece and $L$ is the shear zone length.

**Finite element model**

The aim of the finite element model was to mimic the creasing and folding setups, and to represent cartonboard as a combination of continuum and cohesive models using Abaqus/Standard (ABAQUS, 2008). The four plies were represented by plane strain continuum elements (CPE4), and the three interfaces were represented by a surface formulation using the cohesive behaviour functionality in ABAQUS (2008). A typical model used in the finite element analysis is shown in Figure 6.
Figure 6: A close-up of the FE-mesh at the crease zone and illustration of modelling of the load cell used in the folding experiments.

In the creasing setup, the male ruler and female die were modelled as rigid surfaces. The boundary condition was defined according to the experiments. Hence, the cartonboard was constrained by the clamps in the z-direction, the female die was fixed for all degree of freedom, and the male ruler moved in the z-direction to accomplish the punch movement.

Results and Analysis

Shear strength profile and interface properties

In a previous investigation it has been shown that the shear strength profile for this type of cartonboard is fairly uniform (Nygårds et al. 2009b). This is due to the fact that the two middle plies of this material are mostly made from a CTMP pulp for which plies and interfaces are similar with respect to transverse shear strength. Huang and Nygårds (2011) investigate how the shear strength measurements depended on the shear zone length, $L$. Five sheets were tested for each length, $L = 1.5, 2.5, 5.0, 10, 15, 20$, and $25$ mm. Typical shear strength profiles, i.e. the calculated shear strengths as a function of $z$, for all tests in MD are shown in Figure 7. To illustrate the difference in shear strength as function of shear zone length $L$, the data in Figure 7 have been plotted as box plots in Figure 8 including also the results in CD. The box gives the 75 % confidence interval for the measured data when a normal distribution has been assumed. The line in the box is the median value. The dashed bars represent the 95 % confidence interval. The plus signs represent outliers that were not considered in the fitting to the normal distribution.

In Figures 7 and 8 it can be seen that both the median value and the variation increased as $L$ decreased from 25 to 2.5 mm. For $L = 1.5$ mm, the median shear strength was lower than
the value for $L = 2.5$ mm in both MD and CD. Moreover, the maximum values in Figure 8, represented by the upper bound and the plus signs, in both MD and CD, followed an exponentially increasing trend for decreasing $L$. In addition, it was observed that the shear strengths in MD were roughly 10% higher than in CD. Furthermore, it can be seen that the shear strength profile depended on the shear zone length $L$.

The profiles became more pronounced when the shear zone length, $L$, decreased. This was due to the fact that the test became more local as $L$ decreased. For large $L$ the propagating crack between the notches had a greater tendency to depart from the straight line between the notches, and instead it propagated through weak regions. As a result the fracture surface became uneven.

Moreover, the shear strength increases with decreased $L$. There are two reasons for this. Firstly, as the test becomes more local, higher shear strengths were measured since the failure did not occur in the weakest point of the cartonboard. Therefore, the crack path was straighter for short cracks, as seen in Figure 9. Secondly, short shear zone lengths will be strengthened by fibres that are fixed in the network outside the shear zone. These fibres need to be pulled out of the network at shear failure. For long $L$, the crack can go around these fibres, or any of the two fibre ends can be pulled out of the network. Studies of the fracture surfaces also indicated that test pieces with short shear zone lengths had more pulled out fibres.

For all measurements, bonds were broken and the fibre network was deformed. The measurement of different strengths was due to the fact that different mechanisms were activated, e.g. fibre bridging and localization. In different applications, different of out-of-plane strength data are desirable. In applications where delamination is of concern, measurements with large $L$ are important, since delamination failure will occur along the weakest point, and also can split a paper sheet. On the other hand, in processes that rely on local damage, shear failure at certain positions is desired. Hence, it is necessary to measure local shear strengths with respect to both shear length and position in the thickness direction.

To conclude, problems that depend on local deformation cannot be addressed using test pieces with a large shear zone length. The size dependent shear strength should therefore be put into a perspective of finding new characterization methods that measures properties that are relevant for different applications. If the application is local, the material properties should also be measured locally. In that sense, it can instead be important to consider the variation in measured values as an important and perhaps critical parameter.
Figure 7: Measured shear strengths at different positions in ZD for tests in CD, at different shear zone length $L = 1.5, 2.5, 5.0, 10, 15, 20$ and $25$ mm. Each line represents the measurements from one sheet and $z = 0$ represents the top surface of the cartonboard.
Figure 8: Box plots of shear strength for different shear zone lengths for (a) MD, and (b) CD.
During creasing and folding the cartonboard is loaded locally, and hence data from a short shear zone length would be more appropriate to use in the numerical analysis. In the present numerical simulations, the properties of the interface model was determined using a shear zone length of 5 mm. The shear strengths of the three interfaces, which is different at the different interfaces, were used to set the initial damage shear tractions of the interface model. The values of all related material model parameters are given by Huang and Nygårds (2011).

**Mapping of Continuum Material Properties**

From the characterization of material data for the top, middle and bottom plies (Nygårds, 2008), it is obvious that the different plies have different properties. When characterizing the elastic-plastic properties, it is the average properties of the different test pieces that are measured. In the creasing analysis by Huang and Nygårds (2010) it was assumed that each ply had uniform properties throughout the whole ply. This generated sharp boundaries at the interfaces, since different plies had different properties. This assumption worked well in analysis of the macroscopic creasing behaviour, but initial analysis of folding showed that the interfaces opened up too much.

Huang and Nygårds (2011) investigated the variation in properties in the thickness direction by grinding a 260 mm long cartonboard with a tilted groove in small increments. The resulting surface illustrates the thickness profile of the cartonboard, as shown in Figure 10. It is
obvious from the appearance of the transition zones that the interfaces between the plies are not sharp. Therefore, the material properties (elastic moduli, initial yield stresses and hardening modulus) were in the thickness direction assumed to be described by a second degree polynomial as illustrated schematically in Figure 11. Hence, instead of having uniform properties through the plies; we assigned different properties to each element row in the finite element model. The mapping of data was made such that the average value of each ply still coincided with the measured value and the properties across the interfaces were assumed continuous. Details of this procedure and the resulting material properties used in the finite element analysis are given in Huang and Nygård's (2011).

**Simulation of Creasing and Folding**

Simulation of creasing to \( d = 0.0 \) mm and \( d = 0.2 \) mm was performed in MD and CD. In Figure 12, the numerical results are compared with the corresponding experimental results. The results fitted the experimental results very well during loading and initial unloading. The large continuum shear deformations after the creasing operation can be seen in the contour plots in Figure 13. Especially for the MD test pieces large local shear strains can be observed. This is numerically difficult to handle for anisotropic material models, since the problem becomes ill-conditioned. However, the material mapping techniques did not influence the macroscopic behaviour during the creasing operation.
Figure 14 shows the microscopic structure of the creased and folded zones of two test pieces. It can be seen that the four-ply cartonboard is thoroughly delaminated. The middle plies and bottom plies bulge away from the top ply, and the cartonboard opens up. The middle plies are partly attached to the top and bottom plies, with some fibers crossing through the interfaces. However, in the pictures there are also microscopic delaminations, which not necessary have opened up to comply with the folding constraint. Moreover, the shallow crease depth gave a more triangle-shaped deformation, while the deeper creased test piece gave a more trapezium-shaped deformation.

Folding to 90 degrees was performed both for MD and CD test pieces. The comparison of the rotation moment and rotation angle from the simulations and experiments is shown in Figure 15. The simulation results predict the experimental results well. From the moment-angle curves, we can see that with deeper creasing, the peak value of the bending moment is lowered. Moreover, the bending moment reaches its peak value after 25 degrees. At this stage, the interfaces of the top and middle plies are totally separated. In order to enhance the interpretation of the simulated folding results, Figure 16 shows an example of deformation plots for MD folding at different rotation angles tagged in Figure 15.

When comparing bending moment-rotation angle results with the contour plots it can be observed that the initial bending moment of the creased test pieces comes from folding of the delaminated sample. However, when the peak load has been reached the delamination crack opens up even more, and enables an excessive bulging of the different plies. Thus, the interfaces have opened up so much that the strength of the interfaces are becoming smaller and smaller, and the properties of the cohesive interfaces do not contribute to the slope of the moment-angle curve. For deeper creased cartonboard, the folding profile is smoother, with a lower peak value since the interfaces have been damaged to a larger degree during the creasing operation. In addition, the difference in bending stiffness between \( d = 0.0 \) mm and \( d = 0.2 \) mm, is more pronounced than the difference between MD folding and CD folding. This is because an increased crease depth induces much more interface damage than differences in material properties.

By comparing the microscope pictures in Figure 14 with the final deformed shape contour plots (i.e. MD 00-6 and MD 02-6) in Figure 16, it was observed that the simulations basically captured the shape of the folded cartonboards. For MD folding the interface between top and middle layers opened up more than the other two interfaces. However for CD folding, the largest delamination occurred between the two middle plies.
Figure 12: Comparison between experimental data and simulations for crease depths of 0.0 mm and 0.2 mm for CD test pieces (top) and MD test pieces (bottom). The black solid lines represent simulation with the new material model and dashed blue lines represent experimental results.

**Discussion**

Industrially, there is a need to connect material properties to convertabilty. The deliverables from this research projects, new experimental techniques and numerical finite element simulations, are important tools that enabled us to characterise the through thickness gradient properties of cartonboard and their relations to cartonboard converting. This was done by shear strength profiles and by characterization of different elastic-plastic properties in different plies. There is now an industrial possibility to utilize this knowledge to modify the ply structures and the papermaking process, to optimize cartonboard performance. The shear strength profile is very dependent of process and material alterations. With good
Figure 13: Contour plots of the shear strain components, $\gamma_{xz}$ or $\gamma_{yz}$.

Figure 14: Microscopic picture of the crease zone in a MD test piece after folding. The creasing depth was $d = 0.0$ mm (left) and $d = 0.2$ mm (right), respectively.

engineering skills and a hypothesis of good profiles a substantially improved performance can be achieved. The shear strength can be engineered to be lowest in the plies or along the interfaces. Hence, very different profiles can be engineered, as shown in Figure 17. A well-defined ply structure with weak interfaces give well defined delamination sites, therefore a more pronounced profile should be better than a flat profile. If the shear strength is low, more shear damage will be generated in a paperboard and thereby generate delamination, therefore a vertical shift downwards of the profiles as illustrated in Figure 18 should be
good. A weak position close to the top surface will decrease the tensile stresses at the outer plies, which will decrease the risk for cracking.

Obviously, the tools described in this paper can also be used for parametric investigations of creasing and folding operations. This can be utilised, for example, in trouble shooting to investigate the sensitivity to variations in important process and material parameters.

Conclusions

Creasing and folding of multiply cartonboard were analysed by numerical simulations using the finite element method and shear strength profile data, and the results were compared to experimental data.

In this paper a novel test methods and computation modelling as a tool in product development have been described. The test method does not necessarily provide measurements accurate enough for production quality control. This is partly because it is dealing with the through-thickness properties on which characteristic length scales are of the same order as the fibrous microstructure of the material. However, it provides correctly used in combination with simulations a highly efficient tool for process and materials design that in the end will save time and money in product development. Engineering of interfaces in multiply paperboard structures with optimal interface properties is today no longer a trial-and-error operation, but can be carried out with efficient computation and experimental tools.
Figure 16: Contour plot for MD folding at different rotation angles tagged in Figure 15.
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