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Quasi static analysis of creasing and folding for three paperboards

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Abstract

The creasing and folding behavior of three paperboards have been studied both experimentally and numerically. Creasing and folding studies were performed on strips in both the machine direction and the cross machine direction. A finite element model that mimicked the experimental creasing and folding setup was developed, and the creasing and folding behavior could be well predicted for all three paperboards.

An experimental characterization scheme consisting of three experiments was proposed, and was shown to be sufficient to predict the creasing and folding behavior. For the whole paperboard the shear strength profiles in the through thickness direction was determined with the notched shear test. Each ply was laid free by grinding, and density measurements and in-plane tension tests were performed on the bottom, middle and top plies of each paperboard. Instead of assuming uniform properties in each ply, the shear strength profiles were used to map the measured properties in the through thickness direction.

Numerical simulations were performed when the ply and interface properties of the paperboards were altered to follow different shear strength profiles. This was done in order to mimic different production strategies. It was shown that the interface strengths mainly influenced the folding behavior. Whereas altered the ply properties affected the creasing force needed.

Keywords

Paperboard; Creasing; Folding; Numerical modeling; Shear strength

Introduction

Paper materials are made by spraying wood fiber water suspension on a moving web. Due to the paper making process the fiber form a fiber network that makes paper anisotropic. Most fibers are oriented in the paper machine direction, and very few are oriented in the thickness direction. Commercially made paper materials are often a factor 1-5 stiffer in the machine direction (hereinafter referred to as MD or x) compared to the cross-machine direction (hereinafter referred to as CD or y); and MD is often a factor 100 stiffer than the through thickness direction (hereinafter referred to as ZD or z). (Stenberg and Fellers, 2002)

Paperboard is thick paper qualities that have grammage above 200 g/m². Paperboard can commonly be engineered in the through thickness direction, e.g. by using several different plies, where the fiber treatment and paper making process differ. One design strategy is to

have outer plies with high density, with a low density middle ply. This gives high bending stiffness with as few fibers as possible. Another strategy can be to have strong bottom, top and middle plies and instead have weak interfaces between the plies. This gives paperboard that has well defined delamination sites, which is good from a converting point of view. Most commercially available paperboards have thicknesses in the range 0.20-0.50 mm, where the outer plies have thickness 0.07-0.12 mm.

Since the outer plies often have high density to achieve high bending stiffness it is often the middle ply that is altered to make different qualities of different thicknesses. It is also the middle ply that most commonly is used to design the through thickness profile. The notched shear test has been proposed by Nygård *et al.* (2009a) as a possibility to characterize the ZD-profile in paperboard. The test was further developed by Huang and Nygård (2012).

Converting such as creasing, folding and forming are necessary converting steps to create packages made of paperboard. In the creasing operation a male ruler is pushed into the paperboard, which is placed above a female die that is often about twice as wide as the male ruler. The creasing operation has been experimentally analyzed by Nagasawa *et al.* (2003) and Nygård *et al.* (2009b). The creasing operation generates a very clean shear loading of the paperboard in the region between the tools (Nygård *et al.*, 2009b). Hence, the fiber network deforms and bonds between the fibers break. If the paperboard has well defined shear strength minima, the delamination will mainly occur at these sites as the paperboard is indented. During the subsequent folding, the paperboard will delaminate further since the indented paperboard will bulge out. The creasing is hence a purpose made damage that prevents the paperboard from cracking during folding. Figure 1 illustrates uncreased and creased paperboards that have been folded to 90 degrees. The uncreased paperboard has a discontinuous folding line. The bulging in the folded area is random in the folded area. However, the creased paperboard has an even and sharp folding line which will contribute to better packages.

Figure 1: Microscopical images, seen from the bottom ply, of an uncreased (left) and creased (right) paperboard that has been folded.

Some attempts were made to investigate the creasing and folding mechanisms in the literature. Carlsson *et al.* (1982) used a linear elastic fracture mechanics approach to evaluate the stresses in the creased zone during folding. Xia (2002) used a combination of continuum model and cohesive models to represent paperboard in creasing and folding simulations; the elastic-plastic in-plane continuum model has an anisotropic yield surface

with non-linear hardening functions, while the through thickness continuum model is elastic. Beex and Peerlings (2009, 2012) proposed a linear orthotropic elastic model with isotropic strain hardening and Hill's yield criterion as the continuum model, and a cohesive zone model proposed by Ortiz and Pandolfi (1999), with a cohesive friction model as delamination model. Doeung *et al.* (2012) proposed a model that has different algorithms in different paperboard direction for simulations of creasing and folding. The model used the Ramberg-Osgood model for the in-plane tensile behavior, and Hooke's law for the in-plane compression behavior. All these models have limitations and could not capture all mechanisms activated during the creasing and folding operations. Huang and Nygård (2010, 2012) suggested that a continuum model with orthotropic elasticity and a Hill yield criterion with isotropic hardening, together with a cohesive interface model are sufficient to predict the creasing and folding behavior of paperboard.

Due to the mechanism activated during the creasing and folding operations, the measured shear strength profile is believed to be an important property that should correlate well with good creasing and folding behavior, especially if the delamination sites can be determined a priori. Therefore, paperboards with different shear strength profiles will be used in the experimental and numerical studies.

From previous analysis of creasing (Nygård *et al.* 2009 and Huang and Nygård, 2010) and folding (Huang and Nygård, 2012) we have identified that the continuum plastic properties are important for good predictability of the processes. In this work we therefore aim to characterize only the most important properties needed for creasing, and make sufficient approximations for the remaining properties. The shear strength profiles will be used to generalize the continuum properties in the through thickness direction, which is suggested as a strategy to simplify and minimize the experimental characterization techniques needed to make predictive simulations.

Materials

Three commercially produced multiply paperboards were studied: Paperboards A, B and C, as listed in Table 1. The paperboards were made at different mills, and different strategies have therefore been used to produce the paperboards. Common for all three paperboards was that the two outer plies were stiffer than the middle ply. Different pulps had been used in the different plies to make the paperboards, and the particular boards were chosen since the z-direction design was different.

To determine material properties of the different plies, they were laid free by grinding, following the procedure used by Nygård (2008). Sheets of size 210 mm times 300 mm were ground, such that sheets with free laid bottom, middle and top plies were acquired. The structural properties of the different plies are tabulated in Table 1. The interfaces between plies are not sharp. Instead, the interface region can be up to 0.030 mm thick. During grinding as much as possible of the interface region was removed, as illustrated in Figure 2. Therefore, the total sum of the plies was smaller than the thickness of the whole paperboard. Noteworthy is that Paperboard C differs from Paperboard A and Paperboard B since it is thinner and has higher density. In addition, the density profile in Paperboard C is more uniform than in Paperboards A and B.

Table 1: Thickness and density of the paperboards and the characterized plies.

		Thickness /mm	Density / kg/m ³
Paperboard A	Whole	0.383	66.23
	Top ply	0.065	93.93
	Middle plies	0.180	60.61
	Bottom ply	0.044	87.11
Paperboard B	Whole	0.390	66.05
	Top ply	0.066	109.75
	Middle plies	0.200	63.65
	Bottom ply	0.041	77.19
Paperboard C	Whole	0.332	73.65
	Top ply	0.0518	73.74
	Middle plies	0.156	59.79
	Bottom ply	0.073	71.66

Figure 2: Schematic illustration of the ply and interface structure. As much of the interface region as possible was removed during grinding before testing the plies.

Material model

The numerical model used to represent paperboard had a combination of continuum and cohesive models, as illustrated in Figure 3. The continuum model represents the plies in the paperboard, while the cohesive model accounts for delamination at discrete positions, along the interfaces and within the middle ply.

The plies can sufficiently well be described by an orthotropic linear elastic-plastic Hill model with isotropic linear hardening (Huang and Nygård, 2010). The continuum model is available in Abaqus (2011). The elastic material properties in each ply is hence described by three elastic moduli E_i , three Poisson's ratios ν_{ij} , and three shear moduli G_{ij} . The plastic behavior was described by the yield stresses σ_{ij}^0 , and the linear isotropic hardening modulus H .

The interface model was described by an orthotropic elastic cohesive damage law which relates the interface tractions to the opening and sliding of the interface. The model is available in Abaqus (2011). Each interface has three elastic stiffnesses, where K_{nn} is the stiffness in the interface normal direction, i.e. ZD, and K_{ss} and K_{tt} are the shear stiffness components in MD and CD respectively. In the model the elastic behavior was captured by the continuum model, therefore the elastic stiffness in the interface model was set to be about 5 times stiffer than the continuum model.

Damage was initiated when the maximum stresses needed to initiate damage in the respective directions reached the failure stresses, t_n^0 , t_s^0 and t_t^0 . Hence, a failure stress criterion in each direction, with no coupling between the directions, was used to judge when the damage was initiated, as previously done by Huang and Nygård (2010).

An exponential damage evolution (Abaqus, 2011) was used to account for the softening behavior. When the initiation criterion was reached, the degradation of cohesive strength and damage evolution were initiated. The damage evolution was set by a non-dimensional parameter α and the maximal effective displacement δ_m^f .

Figure 3: Illustration of the numerical model used to represent paperboard.

Experimental set-up

Creasing

On a MTS test rig a creasing device was mounted. It had a male ruler with width 0.7 mm and a female die with width 1.5 mm, as seen in Figure 4. During the creasing experiments, paperboard samples with length 80 mm and width 32 mm were put on the female die, and the male ruler was pushed into the paperboard sample with a loading rate of 1 mm/s to a certain crease depth d . The loading rate in the creasing experiments in comparison to commercial creasing was slow. When the male ruler was pushed through the whole paperboard, the crease depth d was defined to be zero. There were three crease depth tested: $d = 0.0$, 0.2 and 0.4 mm. The positive d -values indicate that the male ruler is below the top surface of the female die.

Folding

To perform the folding experiment, the L&W creasability tester (AB Lorentzen & Wettre, Stockholm, Sweden) was chosen, as shown in Figure 5. One side of the creased paperboard sample was clamped by a rotatable clamp, and 10 mm from the centre of rotation on the other side of crease line, a load cell measured the reaction force during the folding process. The total folding angle was 90 degree, and folding was done at speed of 90 degrees/s.

Finite Element Model

The purpose of the numerical model was to mimic the experimental procedure. Four node plane strain continuum elements (CPE4 in Abaqus, 2011) were used to represent the paperboard continuum plies, which are marked grey in Figure 4. Three layers of interfaces, the red lines in Figure 4, were simulated by a surface formulation using the cohesive behavior functionality in Abaqus (2011). The interfaces were located between the plies and in the middle of the middle ply. In Table 2, the simulated interface position and number of elements in thickness direction for each paperboard can be seen.

The tools used during the creasing and folding experiments, i.e. the male ruler, female die and load cell were defined as rigid surfaces, which are shown in Figures 4 and 5. To make the model simple, the folding boundary conditions used during folding was modeled as a rigid body constrained all clamped nodes of the paperboard and a rotation reference point, instead of modeling the clamping procedure.

The contact between the paperboard model and both the male ruler and the female ruler was defined in the normal and tangential directions, using interaction models in Abaqus (2011). In the normal direction, an exponential overclosure model with contact pressure 0.5 MPa and clearance 10^{-5} mm was used. In the tangential direction, a Coulomb friction model with friction coefficient 1, between the paperboard surface and both the female and male ruler was used. The contact between the paperboard and load cell surface was defined by a Coulomb friction model with friction coefficient 1.

Table 2: Interface position and number of element rows in the thickness direction

	Interface Position* / mm			Number of element rows		
	Interface 1	Interface 2	Interface 3	Top Ply	Middle Ply	Bottom Ply
Paperboard A	0.100	0.200	0.300	6	12	6
Paperboard B	0.100	0.200	0.300	6	12	6
Paperboard C	0.075	0.15	0.225	3	6	3

*The interface position was measured in direction from the top to the bottom surface.

Figure 4: Microscope picture (left) and the FEM model (right) of the paperboard and the creasing tools.

There were two creasing steps: male ruler loading and unloading, where the male ruler was moved downwards and upwards, and the paperboard was unconstrained in the length direction (x for MD samples and y for CD samples). During the folding step, the right side of the paperboard was rotated around a reference point located on left side in the middle of the paperboard of the creased area, as indicated by the red star in Figure 5. The load cell at the left side, above the top surface of paperboard, prevented the paperboard movement as shown in Figure 5.

Figure 5: Folding apparatus (left). Simulation model for folding (right), the red star illustrates the rotation center during the folding process.

Results

Measured material properties

The free laid plies in each paperboard were tested by in-plane tension tests in MD and CD, with four samples for each paperboard. In Figure 6, the stress-strain curves in MD and CD can be found. Testing in the 45 degree direction was also done and is found in the Appendix. In Figure 6, it was observed that the outer plies for Paperboard A and B has similar properties, while Paperboard C differs in the CD direction. The behavior of the middle plies was instead more diverse, mainly because the manufacturing strategies vary much more for these plies. All middle plies do however have lower strength and stiffness than the corresponding outer plies.

From the tensile tests in Figure 6 the elastic modulus E_{xx} and E_{yy} were determined by least square fits to the initial part of the stress-strain curves for the MD and CD tensile test. The initial yield stress for MD, σ_{xx}^0 , and CD, σ_{yy}^0 , were taken as the stresses where plastic strain

was 0.1%. Meanwhile the isotropic hardening modulus H for each ply was taken as the linear curve between the yield point and the failure point of the MD tensile test.

Figure 6: Stress-strain curves from in-plane tensile tests of the top, middle and bottom plies for Paperboards A-C in MD and CD.

The through thickness shear strength profiles were characterized by using the notch shear test (Nygårds *et al.* 2009b), where the shear zone length was 5 mm. For each paperboard 6 samples were used in both MD and CD. By this method, the shear strength gradient in the ZD can be characterized. The test gives the shear strength profiles in the middle ply and in the vicinity of the interfaces (Huang and Nygårds, 2011). Due to the different strategies used to produce the paperboards, the shear strength profiles differ from each other, as seen in Figure 7, where the profiles has been plotted using boxplots (MATLAB, 2010). Paperboard A has a kinky shear profile in the middle ply, which was assumed to be uniform through the ply; Paperboard B has higher strength in the center of the middle ply; and Paperboard C has the lowest strength in the center of the middle ply. For all paperboards the shear strength profile increased in the outer plies. This is however difficult to measure with the notched shear test.

Figure 7: Shear strength profile of Paperboard A, Paperboard B and Paperboard C in MD and CD. Black dash-line indicates the assumed shear strength profile shape for Paperboard A, B and C. The vertical lines indicate the interface locations in the numerical models.

From Huang and Nygård (2010) we know that the shear strength and plasticity are important parameters to predict creasing behavior, and therefore also subsequent folding.

Therefore we want to utilize a simple enough characterization scheme to determine the most important elastic-plastic properties in each ply. The shear strength profiles in Figure 7 were used to determine the shear strengths of the interfaces, t_s^0 and t_t^0 . The positions of the interfaces in the model were used to read the corresponding shear strength in the shear strength profile for the interface. The three positions of the three interfaces used in the models are indicated in Figure 7.

Estimated properties

In this work, two dimensional simulations were used. Therefore the in-plane Poisson's ratios ν_{xy} and the in-plane shear modulus G_{xy} do not influence the results. However, if three dimensional simulations are performed there are good approximations that can be used to estimate these properties, as presented in Equations (A1) and (A2) in the Appendix.

The through thickness Poisson's ratios are close to zero for paper materials (Stenberg and Fellers, 2002). Therefore, it was assumed that $\nu_{xz} = \nu_{yz} = 0$ in all plies.

The through thickness shear moduli and yield stresses have been measured for each ply in Paperboard A (Nygårds, 2008), which has been verified in creasing and folding simulations previously (Huang and Nygårds, 2010). These parameters are difficult to measure accurately, since the delamination can occur before the plastic deformation initiates. Instead of measuring the moduli for all plies, it was assumed that G_{xz} and G_{yz} in Paperboards B and C, would scale in the same way as the in-plane tensile modulus in MD, E_{MD} , in the different plies,

$$G_{ij}^B = \frac{E_{MD}^B}{E_{MD}^A} G_{ij}^A \quad (1),$$

$$G_{ij}^C = \frac{E_{MD}^C}{E_{MD}^A} G_{ij}^A, \quad (2),$$

where G_{ij}^B and G_{ij}^C are the shear moduli G_{xz} and G_{yz} for the plies in the different paperboards, E_{MD} was the measured elastic modulus for the particular ply. In both loading conditions, breaking of bonds between the fibers is the main deformation mechanism, which would validate the approximation.

The initial stresses σ_{xz}^0 and σ_{yz}^0 were approximated using a similar strategy. However, instead of using the elastic modulus, the initial yield stress in MD was used to scale yield stresses that had been measured for Paperboard A, σ_{ij}^{0A} . It was assumed that

$$\sigma_{ij}^{0B} = \frac{\sigma_{MD}^B}{\sigma_{MD}^A} \sigma_{ij}^{0A} \quad (3),$$

$$\sigma_{ij}^{0C} = \frac{\sigma_{MD}^C}{\sigma_{MD}^A} \sigma_{ij}^{0A} \quad (4),$$

where σ_{ij}^0 are the initial yield shear stresses σ_{xz}^0 and σ_{yz}^0 . For completeness that same approximation was also used for the in-plane yield stress σ_{xy}^0 .

The creasing operation loads the interfaces mainly in shear; therefore the opening strength will be of less importance. Therefore, the interface strength in the normal direction, t_n , was assumed to be the same as reported by Huang and Nygård (2011) for all three paperboards.

The elastic modulus in ZD, E_z scales well with density, since higher density usually results in higher E_z . Therefore, the elastic modulus E_z for Paperboard B and Paperboard C were estimated in relation to the elastic modulus and density of each ply in Paperboard A,

$$E_z^B = \frac{\rho_B}{\rho_A} E_z^A, \quad (5),$$

$$E_z^C = \frac{\rho_C}{\rho_A} E_z^A, \quad (6),$$

where ρ_i represents the density of the plies in the three paperboards.

Due to the high degree of anisotropy in paper materials between the in-plane and out-of-plane directions, it is necessary to increase the yield stress in ZD, σ_{zz}^0 , in the numerical simulations. Therefore it was assumed that $\sigma_{zz}^0 = \sigma_{yy}^0$. This approximation ensures that the yield criterion is real. Moreover, in ZD tension the continuum model will not deform plastically, since the delamination model then will open up. It will however increase the yield stress in compression. The experimentally observed compressive behavior of paper materials is however exponential (Nygård, 2008), while the model used here is linear. The approximation therefore works well (Huang and Nygård, 2010).

The elastic stiffness of the interfaces K_{nn} , K_{tt} , K_{ss} and the parameter δ_m^f and α to define softening behavior due to the damage evolution kept as the same value as proposed by Huang and Nygård (2010). All measured and estimated data for each ply and interface are listed in Appendix 1.

Generalization of continuum properties in ZD

In the experimental characterization of elastic-plastic properties, the average value of each ply was determined. The shear strength profiles do however show that the ZD shear strength varies, and there are no sharp boundaries between each plies. The gradient of properties is due to gradients of density. To account for this gradient the elastic-plastic properties was mapped in the ZD utilizing the shear strength profiles, where the condition that the average property would match the measurements was used. The continuum material constants which were tested experimentally, X for each ply were mapped by this

procedure, i.e. $X = [E_{ii}, G_{xz}, G_{yz}, \sigma_{ij}^0, H]$. The procedure has previously been used by Huang and Nygård (2011) to verify folding behavior of paperboard. However, at that time a more complicated algorithm as utilized, which was based on individual measurements of each of the properties. Here mapping functions based on the measured shear strength profiles will be used instead. The shear strength profiles in Figures 7 were therefore represented by polynomial expressions.

The generalization the mechanical properties for the ZD profiles are shown in Figure 8. Based on tensile test results we know that the outer plies are stiffer and stronger than middle plies for all three paperboards. Therefore, the measured shear strength profiles were extended also in the outer plies by linear functions, based on the tensile tests. All profiles then have higher values in the outer plies. The criteria using to perform this generalization is that the average value of mapped material parameters of each ply coincide the measured value of each ply as the horizontal black dash line shows schematically in Figure 8. For each paperboard a mapping function, f_A , f_B and f_C was then defined:

$$f_A(X_{Top}, X_{Mid}, X_{Bot}, C^A, d) = \begin{cases} (C_1^A d + C_2^A) X_{Top} & 0 \leq d \leq 0.116mm \\ C_3^A X_{Mid} & 0.116 \leq d \leq 0.284mm \\ (C_4^A d + C_5^A) X_{Bot} & 0.284 \leq d \leq 0.400mm \end{cases} \quad (7),$$

$$f_B(X_{Top}, X_{Mid}, X_{Bot}, C^B, d) = \begin{cases} (C_1^B d + C_2^B) X_{Top} & 0 \leq d \leq 0.116mm \\ (C_3^B d^2 + C_4^B d + C_5^B) X_{Mid} & 0.116 \leq d \leq 0.284mm \\ (C_6^B d + C_7^B) X_{Bot} & 0.284 \leq d \leq 0.400mm \end{cases} \quad (8),$$

$$f_C(X_{Top}, X_{Mid}, X_{Bot}, C^C, d) = \begin{cases} (C_1^C d + C_2^C) X_{Top} & 0 \leq d \leq 0.10mm \\ (C_1^C d + C_2^C) X_{Mid} & 0.10 \leq d \leq 0.15mm \\ (C_3^C d + C_4^C) X_{Mid} & 0.15 \leq d \leq 0.20mm \\ (C_3^C d + C_4^C) X_{Bot} & 0.20 \leq d \leq 0.30mm \end{cases} \quad (9).$$

Each continuum property, X , used in the model was multiplied with the corresponding mapping function, f , to generate the correct property for each element row in the finite element model. Hence, the variables X_{Top} , X_{Mid} , and X_{Bot} represent the material parameter in the top, middle and bottom ply. The shape of the shear strength profile for each paperboard is represented by the polynomial constants C^A , C^B and C^C , where the superscripts indicate the paperboards names. The variable d is the distance in the thickness direction measured from the top surface.

All mapped material properties for each ply are listed together with the ply data in Appendix 1.

Figure 8: Material mapping profiles for Paperboards A, B and C. The vertical dot-lines represent the boundaries between each ply. The Horizontal dash-lines illustrate the measured value of continuum properties in each ply.

Creasing

The three paperboards were creased in both the MD and CD direction, where MD and CD indicated the direction of the sample; hence the crease is in the perpendicular direction. Three crease depths were used, $d = 0.0, 0.2$ and 0.4 mm, and 3 samples were tested per quality and direction. The force-displacement curves were plotted in Figure 9. Simulations that mimicked the experimental setup were also performed, and the numerical force-displacement curves have also been plotted in Figure 9. The simulation results predicted the experiment force-displacement curves well for all paperboards. Paperboard A and Paperboard B behaved similarly during both MD and CD creasing. Paperboard C had a reaction force that was about 30% less than for Paperboards A and B. In Huang and Nygård (2010), the simulation results did not predict the unloading part of the curves well, but here the predictions became better. The difference was the boundary condition. Here the paperboards were free in the in-plane direction; while in Huang and Nygård (2010) two ends were constrained. The free ends gives less compression in ZD, and therefore, the numerical model predicted the experiments better.

Figure 9: Comparison between experimental data (dotted) and simulations (solid) for creasing depth 0.0 mm (red), 0.2 mm (blue) and 0.4 mm (black) in MD and CD.

Folding

In the folding process it is important that the plies that have delaminated during the creasing operation will bulge inwards and open up the paperboard in the creased area. The major part of this process completes before a rotation of 40 degrees. Therefore, folding up to 40 degrees was analyzed, as seen in the bending moment versus folding angle plots in Figures 10-12, for the three paperboards respectively. For all three paperboards, the simulations predicted the experimental results well in both MD and CD. One could see that the numerical and experimental curves were similar both with respect to shape and magnitude. From the plots, bending stiffness (the slope of the bending moment-rotation angle curve before the maximum bending moment occurs) and maximum bending moment were evaluated, since they are the two important parameters to evaluate folding behavior. Bending stiffness was calculated from the initial linear part of the bending moment-rotation angle curve. With increased creasing depth, both the bending stiffness and the maximum bending moment decreased, since deeper crease depths cause more delamination during creasing. A comparison between the evaluated bending stiffness and maximum bending moment for both the experiments and simulations versus bending stiffness and creasing depth are shown in Tables 2 and 3 for both MD and CD folding. For all three paperboards the bending stiffness and the maximum bending moment are larger in MD than in CD. Paperboard B had the highest bending stiffness among the three. Paperboard A had about 10% smaller, and Paperboard C was roughly 24% smaller bending stiffness than Paperboard B. But the maximum bending moment for Paperboard C was about 50% smaller than the other two paperboards.

In Figures 10-12, it can be concluded that the peak value of bending moment occurred before 20 degrees. Therefore, the contour plots of three paperboards with folding angle 20 degrees were compared with experimentally folded samples with the same angle, as shown in Figure 13. The experimentally and numerically folded samples have similar deformation

behavior. The opening of the interfaces followed the paperboards' respective shear strength profiles, i.e. the weakest interfaces had a larger tendency to open up more. Paperboard A had uniform shear strength in the three interfaces; hence the delamination mostly occurred between top-middle ply and in the middle plies. Due to the compression between the bottom ply and the middle ply, the interface at this area did not opened up. Paperboard B has little higher strength in the middle of paperboard, therefore the interface in the middle opened up less than for Paperboard A. Paperboard C has lowest strength in the middle interface; hence the delamination mainly occurs in the middle interface. Hence, the opening of the interfaces followed the shear strength profiles well.

Figure 10: Comparison between numerical and experiment folding results in MD and CD for Paperboard A.

Figure 11: Comparison between numerical and experiment folding results in MD and CD for Paperboard B.

Figure 12: Comparison between numerical and experiment folding results in MD and CD for Paperboard C.

Table 2: Evaluated average bending stiffness and bending moment for MD folding.

MD Folding			Paperboard A	Paperboard B	Paperboard C
Bending Stiffness /Nm	Creasing depth 0.0 mm	Exp	0.779	0.818	0.618
		Sim	0.735	0.807	0.503
	Creasing depth 0.2 mm	Exp	0.509	0.609	0.357
		Sim	0.603	0.637	0.342
	Creasing depth 0.4 mm	Exp	0.412	0.473	0.246
		Sim	0.436	0.462	0.242
Maximum Bending Moment /Nm	Creasing depth 0.0 mm	Exp	11.88	11.63	6.965
		Sim	11.581	11.983	6.949
	Creasing depth 0.2 mm	Exp	7.68	8.72	5.03
		Sim	8.419	9.249	5.095
	Creasing depth 0.4 mm	Exp	5.493	7.917	3.67
		Sim	5.484	7.631	3.68

Table 3: Evaluated average bending stiffness and bending moment for CD folding.

CD Folding			Paperboard A	Paperboard B	Paperboard C
Bending Stiffness /Nm	Creasing depth 0.0 mm	Exp	0.503	0.534	0.418
		Sim	0.505	0.612	0.419
	Creasing depth 0.2 mm	Exp	0.432	0.457	0.221
		Sim	0.452	0.407	0.298
	Creasing depth 0.4 mm	Exp	0.294	0.292	0.16
		Sim	0.226	0.318	0.158
Maximum Bending Moment /Nm	Creasing depth 0.0 mm	Exp	9.55	8.61	5.81
		Sim	10.056	9.132	5.79
	Creasing depth 0.2 mm	Exp	6.78	6.417	4.5
		Sim	8.206	7.557	5.225
	Creasing depth 0.4 mm	Exp	3.997	3.94	2.21
		Sim	3.7	3.492	2.24

Figure 13: Comparison between experimentally folded samples and FEM contour plots. The folding angle was 20 degrees and the creasing depth was $d=0.0$ mm.

Influence of interface strength on creasing and folding

In the paperboard the interface properties represent the adhesion between the plies. This can be controlled in the manufacturing process e.g. by altering the dryness of the plies or the amount of chemicals used to increase or decrease the bonding ability of different plies. To mimic different manufacturing strategies the interface strength profile was altered. This was done by altering the interface strengths t_n , t_s and t_t in the simulations of creasing and folding in both MD and CD.

Three sets of interface strengths were analyzed for all three paperboards: the measured one, and twice and half the strength of the original measured strengths, as illustrated in Figure 14, which can be written as

$$\mathbf{t}'_A = \alpha \mathbf{t}_A, \mathbf{t}'_B = \alpha \mathbf{t}_B, \mathbf{t}'_C = \alpha \mathbf{t}_C, \quad (10),$$

where t_i represent the new interface strengths of three paperboards, t_i represent the interface strengths which have been measured by experiments, and the parameter $\alpha = 0.5, 1$, and 2. In this case, we can see how creasing and folding performance would change due to strength of the interfaces of paperboard. In the simulations the continuum properties were kept constant.

Figure 14: Simulated shear profiles used to change the interface properties of Paperboard A, B and C. The vertical dot-line profiles represent the boundaries between each ply.

The creasing results was mostly unaffected by the different interface strengths, as seen in Figure 15. There was only a tendency that increased interface strength increased the crease force; roughly doubled interface strengths increased the crease force 5 N for crease depths larger than $d = -0.1$. Moreover, the plastic hardening decreased when the creasing depth reached $d = -0.3$ mm for all three paperboards. In addition, it was noted that high interface strength resulted in more numerical problems, which is seen as the kinks on the creasing curves in Figure 15-17 of MD creasing for all three paperboards. These effects were due to excessive shearing of the continuum element, instead of deforming the interfaces. During the creasing unloading stage the response was unaffected by the interface strengths.

Figure 15: Simulation of creasing with different interface properties of Paperboard A.

Figure 16: Simulation of creasing with different interface properties of Paperboard B.

Figure 17: Simulation of creasing with different interface properties of Paperboard C.

The different interface strengths influenced the folding simulation results significantly. During folding it is important that bending occurs in the creased region, which is most easily achieved when the bending moment of the crease is reduced, and is significantly lower than for the uncreased paperboard. From the folding simulations, the maximum bending moments have therefore been plotted as function of crease depth in Figures 18-20.

In Figures 18-20 it was observed that the interface strengths had an impact on the bending moment, independently of the shape of the shear strength profile. For all paperboards the twice as high shear strengths result in higher bending moments, and the half as small shear strength results in lower bending moments than the measured data. This was due to the fact that less delamination occurred in the interfaces when the strength increased. In addition, it could be observed that all paperboards behaved in the same manner, hence independent on shear strength profile. In Figures 18-20, it was also observed that for MD folding the maximum bending moment initially decreased faster with increased crease depth. But at $d = 0.2$ most of the curves leveled out. While for CD folding there was instead a pronounced decrease of bending moments after $d = 0.2$ mm. For optimal folding performance it therefore becomes important to decrease the interface strength, since that is a secure path to lower bending moments in both MD and CD. High interface strengths would require deeper creases to reach the same amount of delamination along the interfaces.

Figure 18: Maximum bending moment for different interface strengths in Paperboard A evaluated for different creasing depths.

Figure 19: Maximum bending moment for different interface strengths in Paperboard B evaluated for different creasing depths.

Figure 20: Maximum bending moment for different interface strengths in Paperboard C evaluated for different creasing depths.

Influence of continuum properties on creasing and folding

The continuum properties in the paperboard represent the plies. In the manufacturing process the ply properties can be altered by changing the raw material, e.g. the type of fibers or the process, e.g. the degree of beating or the chemicals used in the process. These kinds of changes will generally affect all continuum properties; a denser ply will have higher elastic modulus, yield stress and hardening modulus. Therefore, altered continuum properties were analyzed. This was done by simulating twice as high and half as large continuum properties. This was done by multiplying the measured shear strength profiles, as shown in Figure 21.

Figure 21: Simulated profiles to map continuum properties for Paperboard A, B and C. The vertical dot-line profiles represent the boundaries between each ply.

The relation can be written as

$$\mathbf{X}'_A = \alpha \mathbf{X}_A, \mathbf{X}'_B = \alpha \mathbf{X}_B, \mathbf{X}'_C = \alpha \mathbf{X}_C, \quad (11),$$

where $\mathbf{X}'_i$ represent the new continuum material parameters of three types of paperboards, $\mathbf{X}_i$ represent the original mapped continuum material parameters, and the parameter $\alpha = 0.5, 1, 2$.

The interface properties were however kept constant in the simulations. Simulations of creasing and folding were performed in both MD and CD. During the creasing operation, the continuum properties have larger impact on the force-displacement curves, compared to the interface properties as seen in Figures 22-24. When the continuum properties were doubled or halved, the reaction forces during the loading stage also changed with a similar factor. However, the residual displacement after unloading was not affected much by the change of continuum properties.

Figure 22: Creasing simulation in MD and CD using different continuum properties for Paperboard A.

Figure 23: Creasing simulation in MD and CD using different continuum properties for Paperboard B.

Figure 24: Creasing simulation in MD and CD using different continuum properties for Paperboard C.

From the simulations of folding, as seen in Figures 25-27, it was expected that the bending stiffness would change since the elastic properties of the plies were changed.

Figure 25: Folding simulation in MD and CD using different continuum properties for Paperboard A.

Figure 26: Folding simulation in MD and CD using different continuum properties for Paperboard B.

Figure 27: Folding simulation in MD and CD using different continuum properties for Paperboard C.

In Figures 28-30 the maximum bending moment from the folding simulations have been evaluated as a function of crease depth. It was observed that for shallow creases, $d = 0.0$ mm, there was a large impact of continuum properties on the folding performance. Larger continuum properties resulted in higher bending moments. This was due to the fact that smaller amount of interface damage initiated during creasing process for the paperboard model with larger continuum properties which increased both the bending stiffness and the maximum bending moment for the creased paperboards. However, as soon as the interfaces had been delaminated thoroughly, from $d = 0.2$ mm and deeper, the response from the different continuum properties became similar. This is because the interfaces dominated the behavior, although the plies are stronger and stiffer. In addition, it was

observed that all paperboards had a similar behavior, independently of shear strength profile. For MD folding the bending moment decreased for all α -values, and the effect of decreasing bending moment was largest for $d < 0.2$ mm, especially for the $\alpha=2$ simulations. For CD folding, the effect of α was small when $d > 0.2$, and the effect on bending moment versus crease depth was largest for the simulations with $\alpha=2$.

Figure 28: Maximum bending moment evaluated from the simulations using different continuum properties for Paperboard A at different creasing depths.

Figure 29: Maximum bending moment evaluated from the simulations using different continuum properties for Paperboard B at different creasing depths.

Figure 30: Maximum bending moment evaluated from the simulations using different continuum properties for Paperboard C at different creasing depths.

Discussion

To produce high quality paperboard packages it is important to have a solid understanding of material characteristics, and the paperboard behavior during creasing and folding is essential to predict package performance. It was shown that the material mapping method proposed by Huang and Nygård (2012) could be further simplified, and still be used to predict creasing and folding behavior. Three different paperboards with different properties were used to verify the modeling and characterization concepts. The creasing and folding

behaviors were predicted, when only in-plane tensile tests and density measurements of the bottom, middle and top plies, together with shear strength profiles were used to characterize all essential material properties.

To simplify the characterization of properties new assumptions of material parameter were made for estimation of the through thickness elastic modulus E_z , shear modulus G_{xz} and G_{yz} and the shear yield stress σ_{xz}^0 and σ_{yz}^0 . The through thickness elastic modulus E_z and shear moduli G_{xz} and G_{yz} have only a minor effect on creasing and folding simulations, since plastic deformations dominate the behavior. However, the shear yield stress σ_{xz}^0 and σ_{yz}^0 do influence the simulations. In order to verify the assumption used to estimate σ_{xz}^0 and σ_{yz}^0 , simulations of creasing with doubled and halved through thickness yield stresses were done and compared with experiment results. The altered yield stresses can be written as following functions:

$$(\sigma_{ij}^0)'_A = \alpha(\sigma_{ij}^0)_A, (\sigma_{ij}^0)'_B = \alpha(\sigma_{ij}^0)_B, (\sigma_{ij}^0)'_C = \alpha(\sigma_{ij}^0)_C \quad (12),$$

where $(\sigma_{ij}^0)'_I$ represent the altered shear yield stresses for each ply of the three paperboards, $(\sigma_{ij}^0)_I$ represent the original shear yield stresses, and $\alpha = 0.5, 1$ and 2 . The creasing results have been plotted in Figure 31. The through thickness yield stress σ_{ij}^0 had a large influence on the creasing curves. Altered σ_{ij}^0 changed the creasing force proportionally. The original parameter captured the experiments best for all three paperboards. Thus, the assumption proposed here was adequate to estimate the shear yield stresses. When the results in Figure 31 were compared with the altered continuum properties in Figure 22-24 it was observed that the curve look similar. Hence, altering all continuum properties has the same effect as altering the shear yield stresses, especially when plastic deformation has been initiated. This indicates that the deformation during creasing is shear dominated. Even though the shear yield stresses are important, the experiment to test σ_{xz}^0 and σ_{yz}^0 is not compulsory. The scaling assumption based on Paperboard A is efficient to estimate those material parameters to get good convergence.

The material mapping method was further improved. The through thickness shear strength profile was used for the mapping of continuum properties. The creasing operation is essentially a good shear test (Nygårds et al., 2009b). Therefore, the shear profile is a material characteristic for that should work well to predict creasing and folding behavior. The three types of paperboards were chosen because of their different shear strength profiles. By using three different mapping profiles, the simulation results of creasing and folding gave good predictability of the experiments for all three paperboards.

Figure 31: Creasing simulations with different through thickness yield stresses, compared with experiment results.

When making paperboard there are strategies to alter the interface strengths or the continuum ply properties, which was investigated numerically. The continuum properties had major influence, while the interface strength had a minor influence on the creasing force during loading. However, the change of properties had only minor effect on the residual displacement of the crease. Since the creasing operation is deformation controlled, stiffer and stronger material will require more energy during the operation. Essential during the creasing operations is however that delamination occurs, which is most efficiently evaluated during folding.

During folding we could see that the change of continuum properties had little effect for deep crease depths, while the effect was large for small crease depths. When the continuum material profiles change, the bending stiffness is altered. However, when the paperboard has been creased deep enough the interfaces have become fully delaminated and the interfaces thereafter dominate the folding behavior since the paperboard will bulge out in the creased area. Hence, the amount of delamination initiated during the creasing operation control much of the folding behavior. When the original material properties were used, the amount of delamination initiated by creasing is quite large for all three paperboards. Therefore, we could see that the change of both continuum and interface properties has the largest effect for small crease depths, because the interfaces were not fully delaminated at this stage. All paperboards had also predetermined delamination sites; therefore the effect of the shear strength profiles was moderate. Instead the actual interface strength values influenced the behavior more. In order to lower the bending moment of the crease it was efficient to decrease the interface strengths, rather than to alter the shear strength profile. Here it should however be remembered that we have discrete interfaces, which delaminate easily, as soon as the critical strength has been reached. In reality, the plies are built up by

fibers that can be entangled with each other, and the properties are not uniform along the samples. Hence, to achieve good creasing and folding behavior it is important that the damage propagation along the interfaces or within the plies can take place easily. Due to entanglement this can be difficult. Therefore, the impact of weak shear strength positions in the through thickness direction becomes more important in reality than the simulations in this quasi-static analysis showed. This would be especially important for the high loading rates that are normally used during commercial creasing.

Conclusions

The creasing and folding behavior of three different commercial paperboards was well predicted using two dimensional finite element simulations. In order to determine the material properties in the different plies and interfaces it was shown that it was sufficient to use only three experiments: in-plane uniaxial tensile test in MD and CD of the bottom, middle and top plies, measuring the density of each ply and using the notched shear test to determine the shear strength profile. The shear strength profile was further used to map the properties in the through thickness direction, instead of assuming that each ply had uniform properties.

The interface or continuum properties were altered to mimicking different production strategies for paperboard. It was shown that the interface strengths mainly influenced the folding behavior, whereas altered continuum properties affect the creasing force needed.

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Appendix: Material properties of the plies and generalization of properties in the through thickness direction

In this work, the simulation was done using a two dimensional model. Therefore, the in-plane material parameters, Poisson's ratio ν_{xy} , and in-plane shear modulus G_{xy} , are not needed. However, these material parameters can be well estimated if required. The in-plane Poisson's ratio can be approximated by the empirically relation suggested by Baum *et al.* (1981)

$$\sqrt{\nu_{xy}\nu_{yx}} = 0.293 \quad (\text{A.1}),$$

which can be used together with the symmetry condition of the stiffness tensor

$$\frac{\nu_{xy}}{E_x} = \frac{\nu_{yx}}{E_y} \quad (\text{A.2}).$$

The in-plane shear modulus is difficult to accurately measure from an in-plane shear test for paperboard material. Therefore, it can be calculated by using Hooke's law with the elastic moduli from tensile tests results in the MD, CD and 45 degree direction. The relation can be written as

$$G_{xy} = \frac{1}{\frac{4}{E_{45}} - \frac{1}{E_x} + 2\frac{\nu_{xy}}{E_x} - \frac{1}{E_y}} \quad (\text{A.3}),$$

where elastic modulus in the 45 degree direction E_{45} can be calculated with the same method as E_{MD} and E_{CD} . Tensile tests of the different plies in the 45 degree direction were done and are plotted in Figure A1. The elastic modulus E_{45} was determined by least square fits to the initial part of the stress-strain curves. The value of E_{45} for three paperboards can be found in the following material parameter tables.

Figure A.1: Stress-strain curves from in-plane tensile tests of the top, middle and bottom plies for Paperboards A-C in the 45 degree direction.

Table A.1: Material properties parameters for the top, middle and bottom plies for Paperboard A, and mapped material properties used in the different elements rows in the through thickness direction.

Paperboard A						
	Ply Data			Mapped data from top ply to bottom ply		
	Top Ply	Middle Ply	Bottom Ply			
E_{xx} / MPa	6511.7	3268.5	6962	8133.3; 7322.5; 6917.1; 6106.3; 5700.9; 4890.1; 4890.1; 4079.3; 2459.3; 2459.3; 2459.3; 2459.3; 2459.3; 2459.3; 2459.3; 3730.3; 4192; 5115.6; 5115.6; 6039.1; 6500.9; 7424.4; 7886.1; 8809.6 2271.3; 2082.3; 1987.8; 1798.8; 1704.3; 1515.4		
E_{yy} / MPa	1893.3	1137.4	2569	1515.4; 1326.4; 877.4; 877.4; 877.4; 877.4; 877.4; 877.4; 877.4; 1316.4; 1495.4; 1853.5; 1853.5; 2211.5; 2390.5; 2748.5; 2927.5; 3285.6 5417.9; 4825.9; 4529.8; 3937.8; 3641.8; 3049.7; 3049.7; 2457.7; 1311.6; 1311.6; 1311.6; 1311.6; 1311.6; 1311.6; 1311.6; 1311.6; 2165.9; 2466.2; 3066.7; 3066.7; 3666.1; 3966.9; 4568.1; 4869.6; 5468.9 276.5;255.75;245.375;224.625;214.25;193.5;193.5;1		
E_{45} / MPa	4267.1	1865.6	4233.8	72.75;152;133.375;133.375;133.375;133.375;133.37 5;133.375;152;168.5;185;185;201.5;209.75;226.25;2 34.5;251		
E_{zz} / MPa	235	152	218	75; 67.5; 63.8; 56.3; 52.5; 45; 45; 37.5; 22; 22; 22; 22; 22; 22; 22; 34.8; 39.5; 49; 49; 58.5; 63.3; 72.8; 77.5; 87		
G_{xz} / MPa	60	30	68	0.55; 0.55; 0.55; 0.54; 0.54; 0.53; 0.53; 0.51; 0.49; 0.49; 0.49; 0.49; 0.49; 0.49; 0.49; 0.49; 0.49; 0.49; 0.49; 0.48; 0.48; 0.48; 0.48; 0.48		
ν_{xy}	0.51	0.47	0.45	48.58; 44.39; 42.295; 38.105; 36.01; 31.85; 31.85; 27.675; 23.5; 17.0625; 17.0625; 17.0625; 17.0625; 17.0625; 17.0625; 23.5; 32.2; 40.9; 40.9; 49.6; 53.95; 62.85; 67;75.7		
σ_{xx}^0 / MPa	40.2	23.5	58.3	20.9; 19.1; 18.3; 16.5; 15.7; 13.9; 10.8; 9.4; 6.2; 6.2; 6.2; 6.2; 6.2; 6.2; 6.2; 9.4; 10.6; 13.2; 14.9; 17.7; 19.2; 22.0; 23.5; 26.3		
σ_{yy}^0 /MPa	17.4	8.1	20.6	20.9; 19.1; 18.3; 16.5; 15.7; 13.9; 10.8; 9.4; 6.2; 6.2; 6.2; 6.2; 6.2; 6.2; 9.4; 10.6; 13.2; 14.9; 17.7; 19.2; 22.0; 23.5; 26.3		
σ_{zz}^0 / MPa	17.4	8.1	20.6	8.391; 7.427; 6.967; 5.98; 5.498; 4.534; 1.322; 1.041; 0.76; 0.552; 0.552; 0.552; 0.552; 0.552; 0.552; 0.76; 0.895; 1.03; 2.133; 2.412; 2.552; 2.833; 2.973; 3.254		
σ_{xz}^0 / MPa	2.228	0.38	1.952	30.6; 27.1; 25.4; 21.8; 20.0;16.5; 14.2; 11.2; 8.1; 5.9; 5.9; 5.9; 5.9; 5.9; 5.9; 8.1; 9.6; 11.0; 9.2; 10.4; 11.0; 12.2; 12.8;14.0		
σ_{xy}^0 /MPa	16.86	8.14	16.22	7.552; 6.684; 6.270; 5.382; 4.948; 4.080; 1.190; 0.937; 0.684; 0.496; 0.496; 0.496; 0.496; 0.496; 0.496; 0.684; 0.805; 0.927; 2.030; 2.295; 2.429; 2.696; 2.829; 3.096		
σ_{yz}^0 /MPa	2.005	0.343	1.757	2734; 2462;2325; 2053; 1916; 1644; 2025; 1689; 1018; 1018; 1018; 1018; 1018; 1018; 1018; 1545; 1736; 2118; 1565; 1848; 1989; 2271; 2413; 2695		
H	2189	1353.3	2130.2			
Interface material model parameters						
K_{nn} /(MPa/mm)	776	K_{ss} /(MPa/mm)	2235	K_{tt} /(MPa/mm)	1300	
t_n^0 /MPa	0.28	t_s^0 /MPa	1.1203,1.0389, 1.1073	t_t^0 /MPa	0.9494,0.8712, 0.8712	
δ_m^f /mm	3	α	11.5			

Table A.2: Material properties parameters for the top, middle and bottom plies for Paperboard B, and mapped material properties used in the different elements rows in the through thickness direction.

Paperboard B						
	Tested Data			Mapped data from top ply to bottom ply		
	Top Ply	Middle Ply	Bottom Ply			
E _{xx} /MPa	5647.2	3465.2	7119.4	9561.8; 7604.9; 6625.9; 4668.6; 3689.9; 1732.6; 1732.6; 2598.9; 3032.1; 3898.4; 4331.5; 5197.8; 5197.8; 4331.5; 3898.4; 3032.1; 2598.9; 1732.6; 1732.6; 4426; 5772.7; 8466.1; 9812.8; 12506.2 5026.6; 4065.7; 3585.3; 2624.4; 2143.9; 1183; 1183;		
E _{yy} /MPa	3104.8	2366	2814.5	1774.5; 2070.3; 2661.8; 2957.5; 3549; 3549; 2957.5; 2661.8; 2070.3; 1774.5; 1183; 1183; 1998.8; 2406.6; 3222.4; 3630.3; 4446 7040.3; 5648.1; 4952; 3559.8; 2863.7; 1471.5; 1471.5;		
E ₄₅ /MPa	4255.9	2943	4699	2207.3; 2575.1; 3310.9; 3678.8; 4414.5; 4414.5; 3678.8; 3310.9; 2575.1; 2207.3; 1471.5; 1471.5; 3085.3; 3892.1; 5505.9; 6312.8; 7926 468.5;371.25;322.625;225.375;176.75;79.5;79.5;119.2		
E _{zz} /MPa	274	159	193	5;159;176;193;227;227;193;176;159;119.25;79.5;79.5; 136.25;164.625;221.375;249.75;306.5 88.1;70.05;61.025;42.975;33.95;15.9;15.9;23.8;31.8;35		
G _{xz} /MPa	52	31.8	69.5	.2;38.6;45.4;45.4;38.6;35.2;31.8;23.8;15.9;15.9;42.7;56 .1;82.9;96.3;123.1 0.40; 0.40; 0.40; 0.39; 0.38; 0.35; 0.35; 0.35; 0.35;		
ν _{xy}	0.51	0.47	0.45	0.35; 0.35; 0.35; 0.35; 0.35; 0.35; 0.35; 0.35; 0.35; 0.35; 0.44; 0.45; 0.47; 0.48; 0.49 66.4; 52.8; 46.0; 32.4; 25.6; 12.0; 11.4; 17.0; 19.9;		
σ _{xx} ⁰ /MPa	39.2	22.7	51.5	25.5; 28.4; 34.1; 34.1; 28.4; 25.5; 19.9; 17.0; 11.4; 12.5; 32.0; 41.8; 61.2; 71.0; 90.5 28.0; 22.7; 20.0; 14.6; 11.9; 6.6; 7.3; 10.9; 12.7; 16.3;		
σ _{yy} ⁰ /MPa	17.3	14.5	18.3	18.1; 21.8; 21.8; 18.1; 16.3; 12.7; 10.9; 7.2; 7.7; 13.0; 15.6; 21.0; 23.6; 28.9 28.0; 22.7; 20.0; 14.6; 11.9; 6.6; 7.3; 10.9; 12.7; 16.3;		
σ _{zz} ⁰ /MPa	17.3	14.5	18.3	18.1; 21.8; 21.8; 18.1; 16.3; 12.7; 10.9; 7.2; 7.7; 13.0; 15.6; 21.0; 23.6; 28.9 7.433; 5.889; 5.117; 3.574; 2.802; 1.258; 0.367; 0.550;		
σ _{xz} ⁰ /MPa	2.885	0.367	1.313	0.734; 0.812; 0.891; 1.049; 1.049; 0.891; 0.812; 0.734 0.55; 0.367; 0.760; 2.105; 2.777; 4.121; 4.794; 6.138 54.196; 42.94; 37.313; 26.057; 20.43; 9.174; 7.864;		
σ _{xy} ⁰ /MPa	15.82	7.85	14.87	11.795; 15.727; 17.411; 19.094; 22.468; 22.468; 19.094; 17.411; 15.727; 11.795; 7.864; 6.553; 18.143; 23.938; 35.529; 41.324; 52.914 6.689; 5.300; 4.605; 3.216; 2.522; 1.132; 0.330; 0.495;		
ν _{xy}	2.569	0.330	1.181	0.661; 0.731; 0.802; 0.944; 0.944; 0.802; 0.731; 0.661; 0.495; 0.330; 0.684; 1.894; 2.499; 3.709; 4.314; 5.524 2813; 2237; 1949; 1373; 1085; 510; 610; 915; 1068;		
H	1661.1	1220.6	3056.6	1373; 1526; 1831; 1831; 1526; 1373; 1068; 915; 610; 744; 1900; 2478; 3638; 4213; 5369		
Interface material model parameters						
K _{nn} /(MPa/mm)	776	K _{ss} /(MPa/mm)	2235	K _{tt} /(MPa/mm)	1300	
t _n ⁰ /MPa	0.28	t _s ⁰ /MPa	1.24,1.42, 1.3744	t _t ⁰ /MPa	1.161,1.4623, 1.3711	
δ _m ^f /mm	3	α	11.5			

Table A.3: Material properties parameters for the top, middle and bottom plies for Paperboard A, and mapped material properties used in the different elements rows in the through thickness direction.

Paperboard C					
	Tested Data			Mapped data from top ply to bottom ply	
	Top Ply	Middle Ply	Bottom Ply		
E_{xx} /MPa	9223.8	3122.1	5875.6	13948.7; 9223.8; 4498.9; 4498.9; 3122.1; 2261.6; 2089.5; 2261.6; 4498.9; 4498.9; 5875.6; 7252.3	
E_{yy} /MPa	5640.9	768.6	2470.5	9662.2; 5640.9; 1619.6; 1619.6; 768.6; 236.7; 130.4; 236.7; 1619.6; 1619.6; 2470.6; 3321.6	
E_{45} /MPa	6441.3	1430.7	3809.7	10262.4; 6441.3; 2620.2; 2620.2; 1430.7; 687.3; 538.6; 687.3; 2620.2; 2620.2; 3809.7; 4999.2	
E_{zz} /MPa	184	150	179	201;184;167;167;150;133;135.4;150;164.6;164.6;179.2;193.8	
G_{xz} /MPa	85	28.7	57.4	127.225;85;42.775;42.775;28.7;14.625;21.525;28.7;35.875;35.875;57.4;78.925	
ν_{xy}	0.51	0.47	0.45	0.35; 0.37; 0.49; 0.49; 0.59; 0.91; 1.17; 0.91; 0.49; 0.49; 0.45; 0.43	
σ_{xx}^0 /MPa	53.4	28.81	34	65.695; 53.4; 41.105; 41.105; 28.81; 16.515; 26.215; 28.81; 31.405; 31.405; 34;36.595	
σ_{yy}^0 /MPa	25.9	5.4	12.8	42.35;25.9;9.45;9.45;5.4;1.35;2.7;5.4;8.1;8.1;12.8;17.5	
σ_{zz}^0 /MPa	25.9	5.4	12.8	44.4; 25.9; 7.4; 11.4; 5.4; 1.7; 0.9; 1.7; 11.4; 8.4; 12.8; 17.2	
σ_{xz}^0 /MPa	1.885	0.466	1.788	3.641; 2.960; 2.278; 0.664; 0.466; 0.267; 0.424; 0.466; 0.508; 1.052; 1.139; 1.225	
σ_{xy}^0 /MPa	21.59	9.98	10.219	26.550; 21.581; 16.612; 14.239; 9.980; 5.721; 9.081; 9.980; 10.879; 9.066; 9.815; 10.564	
ν_{xy}	1.696	0.419	1.609	3.277; 2.664; 2.05; 0.598; 0.419; 0.240; 0.381; 0.419; 0.457; 0.946; 1.025; 1.103	
H	2504.2	1224	1767	3080; 2504; 1927; 2140; 1500; 860; 1365; 1500; 1635; 1632; 1767; 1901	
Interface material model parameters					
K_{nn} /(MPa/mm)	776	K_{ss} /(MPa/mm)	2235	K_{tt} /(MPa/mm)	1300
t_n^0 /MPa	0.28	t_s^0 /MPa	1.6724,0.9966,1.1464	t_t^0 /MPa	1.008,0.6709,0.8712
δ_m^f /mm	3	α	11.5		