Delamination in the scoring and folding of paperboard

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ABSTRACT: Delamination between layers occurs during the creasing and subsequent folding of paperboard. Delamination is necessary to provide some stiffness properties, but excessive or uncontrolled delamination can weaken the fold, and therefore needs to be controlled. An understanding of the mechanics of delamination is predicated upon the availability of reliable and properly calibrated simulation tools to predict experimental observations. This paper describes a finite element simulation of paper mechanics applied to the scoring and folding of multi-ply carton board. Our goal was to provide an understanding of the mechanics of these operations and the proper models of elastic and plastic behavior of the material that enable us to simulate the deformation and delamination behavior. Our material model accounted for plasticity and sheet anisotropy in the in-plane and z-direction (ZD) dimensions. We used different ZD stress-strain curves during loading and unloading. Material parameters for in-plane deformation were obtained by fitting uniaxial stress-strain data to Ramberg-Osgood plasticity models and the ZD deformation was modeled using a modified power law. Two-dimensional strain fields resulting from loading board typical of a scoring operation were calculated. The strain field was symmetric in the initial stages, but increasing deformation led to asymmetry and heterogeneity. These regions were precursors to delamination and failure. Delamination of the layers occurred in regions of significant shear strain and resulted primarily from the development of large plastic strains. The model predictions were confirmed by experimental observation of the local strain fields using visual microscopy and linear image strain analysis. The finite element model predicted sheet delamination matching the patterns and effects that were observed in experiments.

Application: Accurate material models for paper deformation are useful in predicting sheet delamination effects in converting operations. This work provides a better understanding of the factors controlling delamination during scoring and folding of paperboard.

In many converting processes, such as scoring and folding, paperboard is subjected to high magnitude stresses and undergoes large deformation in three dimensions. Several recent studies have analyzed the behavior of paperboard under such large stress conditions. An example is the recently reported study of corner fold development [1] in liquid board packages. When paperboard is folded in making a liquid packaging carton, the uniformity and quality of the fold are improved by scoring it (also known as creasing) to introduce plastic deformation and some delamination, which allows for more controlled bending during the subsequent folding operation. Although the importance of scoring has long been recognized, a good understanding of the physics has been lacking. Nagasawa et al. [2] studied scoring and folding experimentally to obtain a more fundamental understanding of the operations and its effects on paperboard. They found that the depth of the score is a major factor affecting the bending moment during subsequent folding. They were able to characterize scoring geometry and aspects of delamination with the folding resistance.

Although experimental work can provide substantial insight into converting processes, the use of finite element analysis can enhance this understanding and provide a convenient optimization tool. Therefore, simulation of the scoring operation and its effect on the paperboard, including its delamination, can serve an important purpose. For accurate analysis, though, valid material models for the paperboard must be used, particularly those that reflect paper's nonlinear plasticity, strong anisotropy, and differential response to loading and unloading conditions.

The tensile deformation behavior of paper in the in-plane directions (machine direction [MD] and cross direction [CD]) is well known. However, the out-of-plane deformation mechanics of paper only recently have been analyzed carefully [3], and suitable mechanical models have been proposed. Many models for materials, including plasticity, are available for incorporation into finite element analyses. An example is Hill's model [4], incorporating 17 parameters. The Hill model is anisotropic, but supposes a similar behavior of the material in all three material directions, which is not observed in paper. Paper is an anisotropic material exhibiting very different mechanical properties in its principal directions. The model also does not allow for any differences in material deformation under tension and compression, which is also invalid for paper. However, this model was used widely for folding simulation in work of Barbier et al. [5], and for creasing and folding problems in works of Gooren [6] and Beex and Peerlings [7].

Xia [8] and Xia et al. [9] developed a different material model that takes into account the differences in the material behavior under tension and compression. In-plane deformation of paper is considered as elastic-plastic and the out-of plane compression and tension are independent of the in-plane stress-strain state. The total number of material parameters is larger in comparison with Hill's model, and the numerical implementation of this model requires a complicated calibration procedure [10]. Examples of creasing and folding simulations using this model are presented in the works of Xia [8], Elison and Hansson [10], and Nygårds et al. [11].

Stenberg [12] developed an elastic-plastic model for shear and compression loading of paper where the yield surface was obtained by scaling the failure stress surface. Work hardening also was included by allowing the yield surface to grow. The model can be included in models such as those of Xia et al. [9] to handle out-of-plane deformation. Welp et al. [13] present an analysis of the out-of-plane deformation of paper using a material model similar to that of Stenberg.

Mäkelä and Östlund [14] proposed a model for paper plasticity based on concepts developed by Karafillis et al. [15] for anisotropic materials. They defined an equivalent isotropic stress state by applying a linear transformation to the actual anisotropic stress in the material and tracked the yield behavior in this transformed stress space. This concept, known as the isotropic plasticity equivalent (IPE) for the anisotropic material, has proven quite useful in studying deformation of paper. Mäkelä and Östlund applied the Ramberg-Osgood model to describe paper deformation in all three material directions and shear as well. The two principal parameters of the model, the hardening modulus and the hardening exponent, are used and assumed to be the same for load-deformation curves in all the directions. In the model, deformation under tension and compression do not differ, which is opposite to experimental observations. This model was used by the authors for plane stress-state simulations only. No applications for creasing and/or folding of paper were found.

In this paper, we report results of numerical simulation of creasing and folding of paperboard based on incorporating the complexity of the z-direction (ZD) stress-strain relations together with the Ramberg-Osgood plasticity relation in the MD and CD.

Material model

Paper is considered to be orthotropic. Examples of stress-strain deformation curves of paperboard can be found in numerous studies [6-12,14,16]. The character of material deformation under tension and compression in each of the material directions is different. In-plane and out-of-plane deformation behavior also differs.

We used the Ramberg-Osgood model for the tensile curves in MD and CD under loading. This model defines the strain in MD or CD as a function of the appropriate stress with three parameters:

$$\varepsilon_i = \frac{\sigma_i}{E_i} + \left(\frac{\sigma_i}{E_0}\right)^n \tag{1}$$

Here E_0 is the hardening modulus, n is the hardening exponent, ε_i is the strain component in MD or CD, σ_i is the correspondent stress component, and E_i is the elastic (Young's) modulus in direction i. For unloading, we used Hook's law:

$$\varepsilon_i = \frac{\sigma_i}{E_i} \quad . \tag{2}$$

The compression curve in any in-plane material direction is described by Hook's law, Eq. (2), up to pick stress limit (loading after this limit leads to strain softening).

For the ZD test, we used a power law to describe the stress-strain curve under compression. Compression in ZD during loading was described by

$$\sigma = a\varepsilon^{a} , \tag{3}$$

where a = 26.898 MPa represents the loading amplitude and α = 1.49, the loading exponent. During unloading, we used

$$\sigma_{zz} = b(\varepsilon - \varepsilon_0)^{\beta} , \tag{4}$$

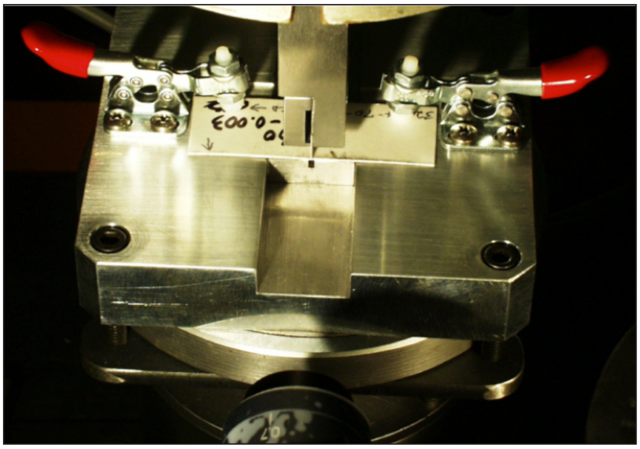
where $b = c\varepsilon^{\gamma}_s$ represents the unloading amplitude, for which c = 48.63 MPa and γ = -0.38; $\beta = -1.0234\varepsilon_s + 2.4$ is the unloading coefficient, where ε_s is the strain value corresponding to the beginning of the unloading step; and ε_0 is the strain value corresponding to zero stress during the unloading step (i.e., the reference strain). This reference strain is given by the following equation:

$$\varepsilon_0 = \varepsilon_s - \left(\frac{a}{b}\varepsilon_s^{\alpha}\right)^{1/\beta} . \tag{5}$$

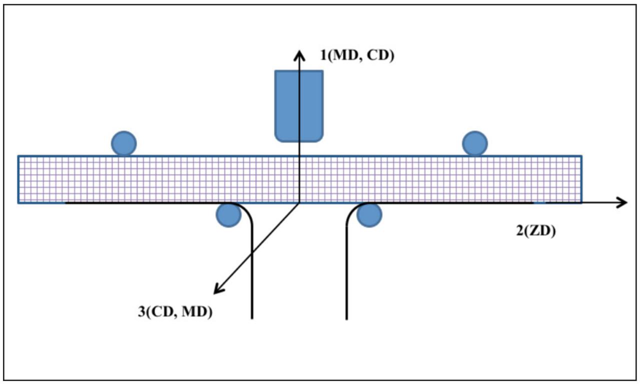
Tensile behavior in ZD and all shear behaviors are purely elastic until the elastic limit, as described by Eq. (2). Nonlinear behavior of the material was implemented in the algorithm of plane-strain elastic-plastic deformation with kinematic hardening [17]. The algorithm was adapted for the orthotropic materials by using an isotropic plasticity equivalent (IPE), introduced by Karafillis et al. [15].

EXPERIMENTAL

We used paperboard with a basis weight of 310 g/m² for the experiments and numerical simulations. **Figure 1** shows the actual test fixture. The female die had a width of 1.9 mm; the corners were rounded, with a radius of 0.25 mm. The male rule had a width of 0.56 mm, and the corners were rounded, with a radius 0.125 mm.



1. Experimental setup for paperboard creasing.



2. Finite element scoring and folding model in initial configuration.

The specimens were placed in the testing fixture (Fig. 1). Vertical movement was restricted at ends of the specimen by stoppers, but the specimen was free to move laterally.

Finite element model

The one principal feature of this setup was the location of the paperboard sample with one of the in-plane material directions coincident with the x axis (**Fig. 2**) and with ZD coincident with the y axis. The size of the domain for simulations was chosen to be the central part of the sample where creasing occurs. This was selected to be 8 mm in total length, centered about the rule. Because paper is orthotropic, in the numerical modeling we do not need to consider the general three-dimensional case, only the two-dimensional plane strain case. The numerical solution to the creasing-folding transient problem was determined using the commercial finite element code ABAQUS/Explicit [17]. The material model of paperboard was implemented using the user subroutine VUMAT.

The bodies of male rule, female die, and stoppers were considered as rigid bodies, and the paper sample was divided into quadrilateral four-node plane-strain elements. To check the convergence of the solution, three different finite element grids with element size (height and length in initial undeformed state) 0.05 mm, 0.025 mm, and 0.01 mm were considered. We found that the latter two grids give similar results (calculated difference in stress components was less than 15%). Therefore, most of our simulations were performed with 0.025 mm elements, with 18 layers of elements in the thickness direction and a total of 5472 elements. The boundary conditions for the creasing problem were specified as contact conditions of the sample with rigid surfaces of the female die, male rule, and the upper stoppers. For the folding problem, the contact boundary conditions were changed; the female die and male rule were replaced with two wire stoppers installed below the paper sample and moved in the upward direction. The friction coefficient on all contact surfaces was selected to equal 0.1.

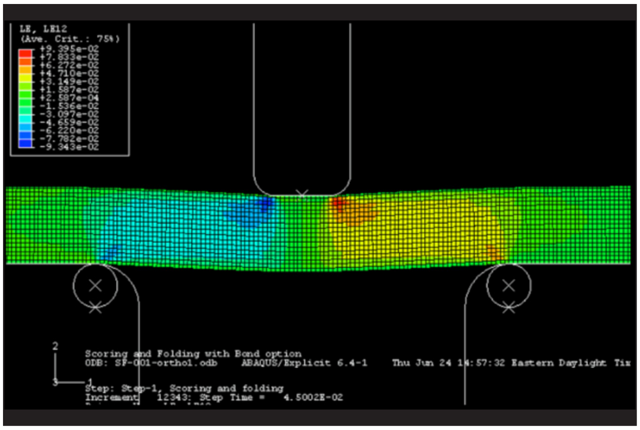
Property	Value
Elastic modulus in MD, tension, MPa	4.65×10^3
Elastic modulus in CD, tension, MPa	1.77×10^3
Elastic modulus in ZD, compression, MPa	40.21
Elastic modulus (shear) in MD-ZD, MPa	1.72×10^3
Elastic modulus (shear) in CD-ZD, MPa	0.6×10^3
Hardening modulus in MD, MPa	206
Hardening modulus in CD, MPa	17.2
Hardening exponent in MD	2.867
Hardening exponent in CD	4.460
Peak stress in ZD, MPa	0.655
Peak shear stress (MD-ZD), MPa	1.0
Poisson ratio MD-ZD	0.01
Poisson ratio MD-CD	0.3
Poisson ratio ZD-CD	0.01

I. Mechanical properties used in the simulations.

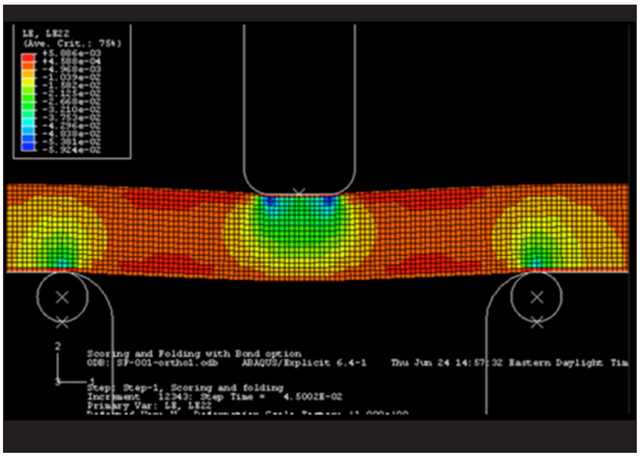
To take the delamination effect into account, bonding layers were inserted between each horizontal layer of finite elements. Two criteria for delamination were used: maximum uniaxial shear force and maximum uniaxial normal force (in our case, in the ZD). The first of these conditions works mainly during the creasing stage during loading (delamination initiation). The second one is the delamination propagation mechanism during folding. This delamination algorithm is similar to the cohesion algorithm described by Xia [8] and Nygårds [11]. The maximum force criteria were calculated from the peak stresses in **Table I**.

RESULTS

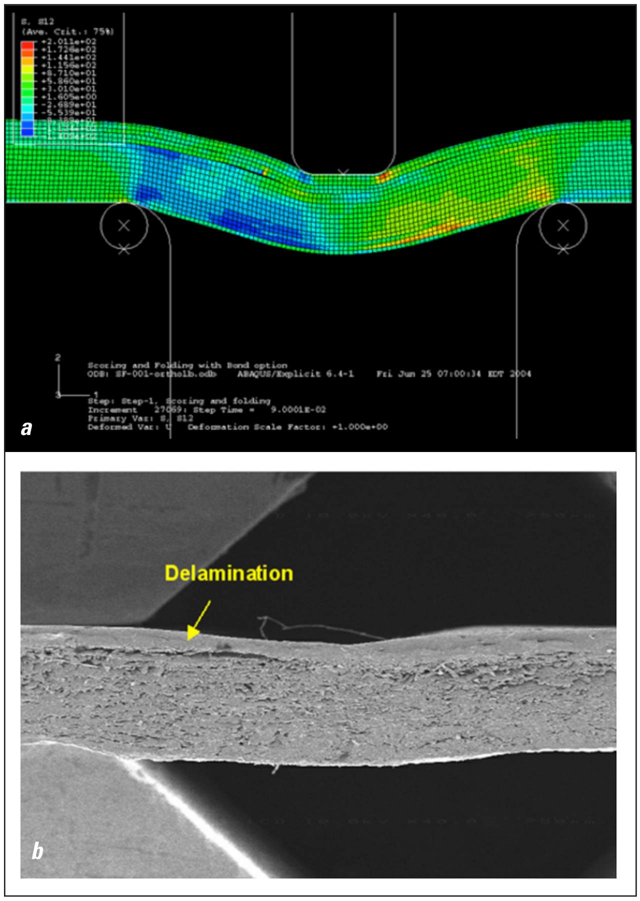
Table I shows the set of parameters obtained from the uniaxial testing of the board sample [16]. Numerical simulations of



3. Shear strain predictions from the finite element model.



4. Z-direction (ZD) strain predictions from the finite element model.



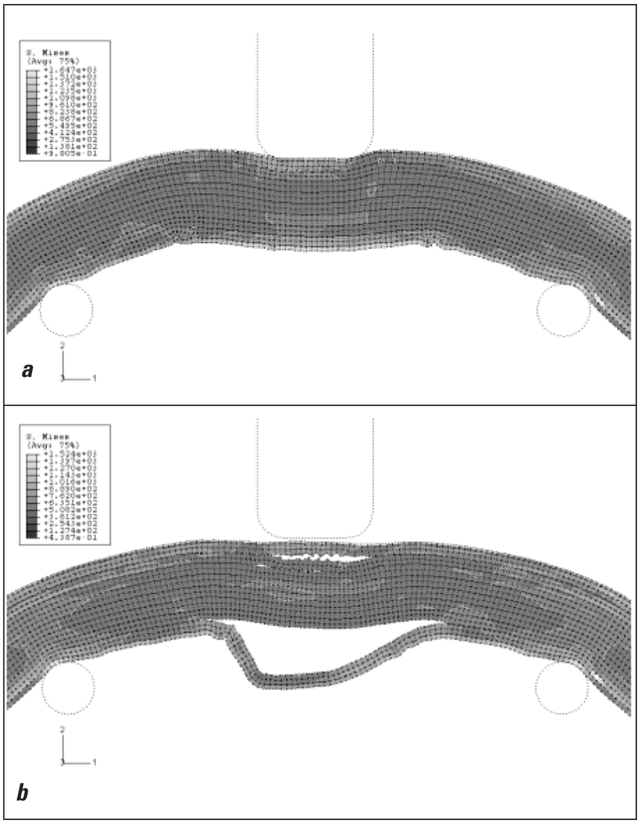
5. Delamination during scoring: a) delamination took place near the printed side around the rule at 75% of the maximum score depth, unloading; b) delamination observed in a carton sleeve.

creasing and folding problems were performed using commercial finite element code ABAQUS/Explicit [17]. Although the initiation of delamination cannot be observed experimentally, it can be identified in the numerical simulations by analyzing the predicted strains. **Figure 3** shows the shear strain field predicted by the model. **Figure 4** shows the ZD strain field. Shear strain distribution was symmetrical and varied from -2% to 2% (Fig. 3). ZD strain that was predicted by the finite element model was plotted from -3 to 0.1% (Fig. 4). Such predictions are useful in understanding the effect of the scoring process and the strain conditions preceding delamination. The strain fields are symmetrical about the vertical axis (Figs. 3 and 4). However, later in the process, the strain field became asymmetric and nonhomogeneities developed. Higher deformation levels could lead to delamination.

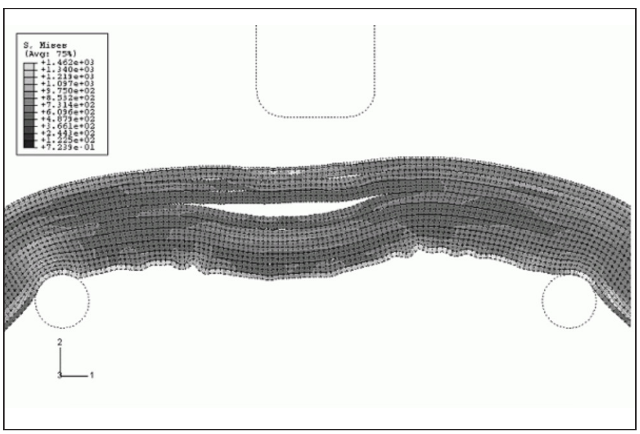
Figure 5 shows delamination occurring during the scoring process as a result of excessive shear stresses. Figure 5a shows the predictions during unloading, whereas Fig. 5b is an example of what is observed experimentally. Delamination occurs in the tip region. Using the same model, we also investigated the folding process. **Figure 6** shows results for a single-ply paperboard. The fracture plane had the identical fracture criteria used in the scoring process and any failure that occurred in the scoring process was carried into the folding process. Figure 6 illustrates that ZD tensile and shear strength can affect delamination under the given mechanical properties and boundary conditions. When shear strength was high, not much delamination was observed in the model predictions (Fig. 6a). When the shear strength was somewhat lower, the model showed delamination (Fig. 6b). The results also show that delamination would occur mainly during the scoring process as a result of shear. **Figures 7** and **8** show delamination after folding was completed for a three-ply paperboard. The top and bottom plies have identical elastic and plastic properties and the fracture plane introduced in both plies was identical. The maximum ZD bond strength in the mid-ply was chosen as 413.4 kPa and the finite element analysis was conducted. Delamination also can develop as more plies are involved (Fig. 6).

CONCLUSION

Using finite element simulations, we were able to analyze the scoring and folding of paperboard. Recently developed ac-

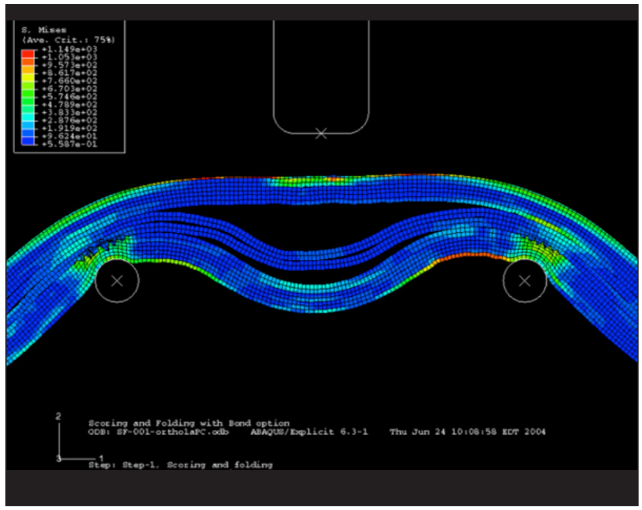


6. Delamination pattern after folding of a single ply sheet: a) the maximum ZD tensile strength is 275.6 kPa and maximum shear stress is 5512 kPa; b) the maximum ZD tensile strength is 689 kPa and maximum shear stress is 2756 kPa.



7. Delamination patterns in three-ply board after folding. The maximum bond strength in the top and bottom plies is 827 kPa in the ZD and 2412 kPa in shear. The maximum bond strength in the mid-ply is 413.4 kPa in the ZD and 2067 kPa in shear. Rule score depth: 0.7366 mm.

curate material models for paper deformation were quite useful in predicting sheet delamination effects in converting operations. The evolution of delamination and its patterns can be tracked using simulation tools, provided that the material models reflect the complexity of paper adequately. **TJ**



8. Delamination patterns in three-ply board after folding. The maximum bond strength in the top and bottom plies is 689 kPa in the ZD and 3445 kPa in shear. The maximum bond strength in the mid-ply is 551.2 kPa in the ZD and 1240.2 kPa in shear. Rule score depth: 0.8255 mm.

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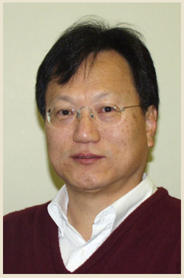
Delamination is an important problem in converting, particularly with forming containers. The techniques presented in this work provide a better understanding of the main contributions to package failure.

The most difficult part of this research was developing a proper constitutive relation for paper that accounted for anisotropic plasticity. The most interesting result was the relatively large impact of in-plane properties as compared to z-directional tension on the delamination.

It is possible to obtain controlled delamination and product performance by carefully tuning the mechanical properties of the sheet. Critical properties and their impact can be judged using this simulation. In future work, we will pursue application of these techniques to study the behavior of packaging and optimize performance.



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