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MODELING THE CREASING OF PAPERBOARD

JAAN-WILLEM SIMON*, YUJUN LI AND STEFANIE REESE

Institute of Applied Mechanics, RWTH Aachen University
Mies-van-der-Rohe-Str.1, 52074 Aachen, Germany
*e-mail: jaan.simon@rwth-aachen.de, www.ifam.rwth-aachen.de

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Abstract. Laminated paperboard is widely used in packaging products. It usually consists of multiple layers bonded to each other by starch or adhesive materials. To obtain the commercial cartons with high quality, the indentation of fold lines (creasing) plays a crucial role during the whole converting processes. Thus, the aim of this study is to describe the material behavior of a laminated paperboard during the creasing process. The paperboard was considered as a laminate of three different layers, each of which was modeled separately with an anisotropic elastic-plastic material model. The initial yielding was given by the Hill’s 48 yield criterion, while the isotropic strain hardening was described by a power law hardening function. To calibrate the material parameters, a sequence of tensile tests was conducted for each layer in different directions to account for the material’s anisotropy. Furthermore, tensile tests for the whole laminate were performed, such that numerical predictions could be validated against experimental data. Finally, the creasing process was investigated using a two-dimensional finite element model with a plane strain assumption.

1 INTRODUCTION

Laminated paperboard is widely used in packaging products such as toys, beverage and frozen foods. Its most beneficial characteristics are low price, sustainability, and straightforward manufacturing process.

To obtain the commercial cartons with high quality, it is the indentation of fold lines (creasing) that plays a crucial role during the whole converting processes. A good crease is to introduce damage in the paperboard to locally reduce its bending stiffness and to prevent the board from breaking during following processes [1]. However, the breaking of the top layer is a frequent problem, especially for high grammage layer, which renders packages less appealing to customers and compromise its strength as well. Therefore, it is essential to study the paperboard creasing process.

The laminated paperboard under consideration consists of multiple layers, each of which is composed of a network of bonded fibers. The layers are bonded to each other by starch or adhesive materials. The preferential microscopic fiber orientations result in a highly anisotropic mechanical behavior, including anisotropic elasticity, initial yielding, strain hardening, and tensile failure strength [2]. The principal directions are given by the machine direction (MD), cross direction (CD) and out-of-plane direction (ZD), see Fig. 1. According to experimental investigations performed by Stenberg and Fellers [3], the stiffness in MD can be 1–5 times higher than the stiffness in CD, and 100 times higher than the stiffness in ZD.

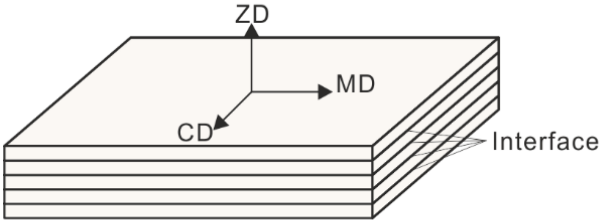

Figure 1: Principal directions of laminated paperboard

In the literature, one can find several material models which have been proposed to describe the anisotropic mechanical behavior of paperboard. For example, Xia et al. [2] used an anisotropic yield surface with non-linear hardening functions, where plasticity was initiated by a multi-surface function constructed from yield planes for tension and compression in MD, CD and ZD, as well as shear. The natural drawback of such complex models is the extensive experimental effort required for the calibration of parameters. Alternative approaches describe the yield surface based on the Tsai-Wu criteria; see e.g. the one proposed by Harrysson and Ristinmaa [4]. This model is based on biaxial tension tests of liner and fluting.

Furthermore, several studies have been performed to obtain insight into the creasing of paperboard. Beex and Peerlings [1] have demonstrated the mechanisms that occur in paperboard during creasing and folding by means of experimental observations and numerical analyses of a mechanical model. Based on that, they studied the influence of delamination on creasing and folding and revealed the separate role of the cohesive zone model and the friction model in the description of delamination [5]. Other works dealing with the delamination in paperboards can be found e.g. in [6, 7]. In addition, the large bending behavior of creased paperboard has been investigated recently by Mentrasti [8], whereas the folding behavior of creased paperboard has been treated numerically by Giampieri et al. [9] as well as by Huang et al. [10].

In this work, the paperboard creasing process is investigated, where the crease lines run in the MD direction. On the basis of an orthotropic elastic-plastic constitutive model for each layer, a 2D finite element model is employed to predict the paperboard’s response in its creasing process.

2 EXPERIMENTALLY OBSERVED BEHAVIOR

2.1 Characterization of paperboard

The paperboard examined in this paper consists of five fiber plies and two pigment plies, as shown in Fig. 2. In order to model the paperboard, the mechanical properties of the constituent plies are essential. These properties can be determined by performing experiments on the single plies of the laminate separately. However, it is difficult to separate the pigment from the front ply, and the three middle plies from each other. Consequently, the laminate is considered as being composed of three layers only: the front layer, consisting of the two pigment plies and the front ply, the middle layer, consisting of the three middle plies, and the back layer. These layers can be separated mechanically for individual evaluation.

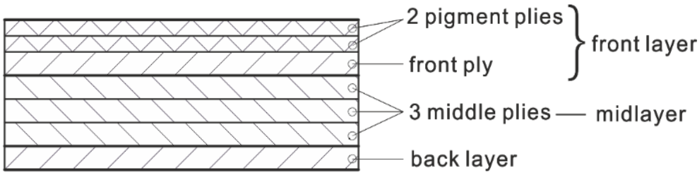

Figure 2: Schematics of paperboard layup

Due to the continuous nature of the paper manufacturing process, fibers are primarily oriented in the plane. Additionally, within the plane, fibers are more highly oriented in the MD than the CD. Furthermore, the outer layers are typically stiffer and stronger than the inner ones. Thus, testing and modeling is applied separately for each of the three distinct layers. As a result, the deformation behavior of the paperboard laminate will be presented in terms of its effective composite behavior.

2.2 Elastic-plastic behavior of paperboard

To characterize the material behavior of the single layers, tensile tests were conducted for each layer in the machine direction (MD) and cross direction (CD) as well as in the 45° direction. The tensile test samples were cut from a large sheet. The shape and dimensions of the test samples followed the standard ISO 1924-2:2008 except for the width. The latter was changed for each layer, because the width had to include a sufficient amount of fibers in order to behave as a homogeneous material. Moreover, it should be high enough to avoid the influence of thickness variation in samples due to the mechanical separation process.

A group of uniaxial tensile test study on 200mm long pieces was performed in CD. Different choices of test piece widths, ranging between 10mm and 45mm, were tested. The results are presented in Figure 3. The stress–strain plot shows the average behavior of 10 tests for each choice of test piece width. The differences in the measured material behavior were found to be not that significant among the several choices of test piece widths. However, it was necessary to choose the 30mm wide or even wider test pieces in order to get better results. In the following, 30mm wide test pieces were used.

The in-plane uniaxial tensile stress–strain curves for the MD, the CD and an orientation 45° are plotted together in Figure 4. These stress–strain curves clearly depict the difference in the modulus and initial yield strength between MD and CD. Since the out-of-plane properties are difficult to measure, they have been adopted as those for the CD direction. However, the influence of this assumption should be further investigated in future work.

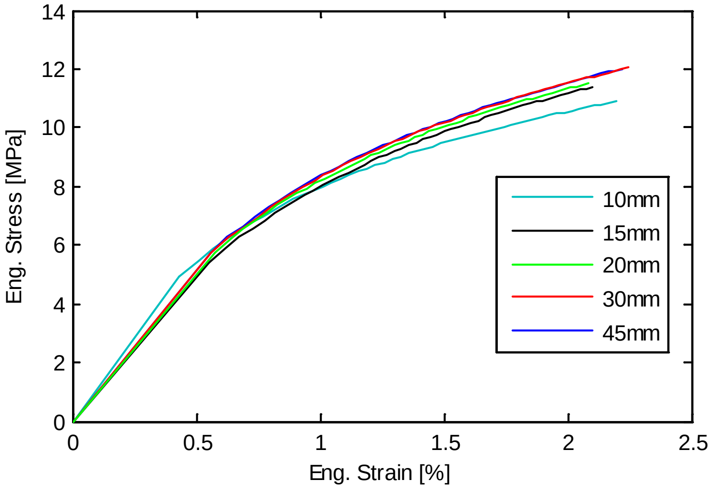

Figure 3: Uniaxial material behavior in CD with variation of test piece width [mm]

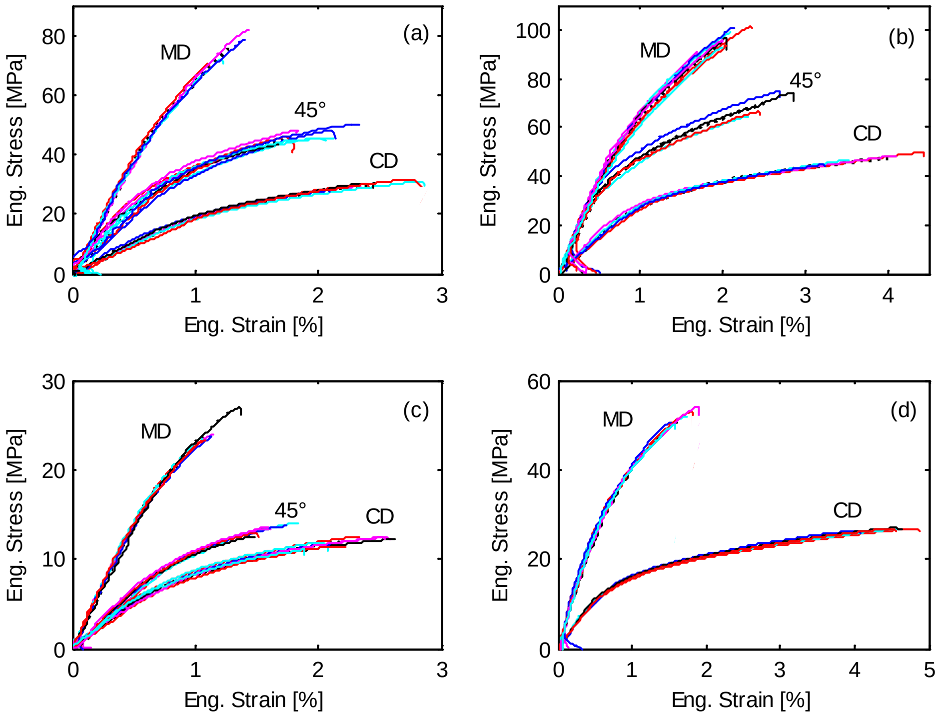

Figure 4: Experimental results (solid) and fits (dashed) for the: (a) back layer, (b) front layer, (c) midlayer, and (d) paperboard

Finally, to illustrate the plastic material behavior and to distinguish it from potential damage, loading-unloading curves have been measured for different samples, as shown in Fig. 5. Therein, an initial yield point is visible as well as a significant amount of permanent strain upon unloading. Such behavior can be accurately described by using conventional elastic-plastic constitutive models.

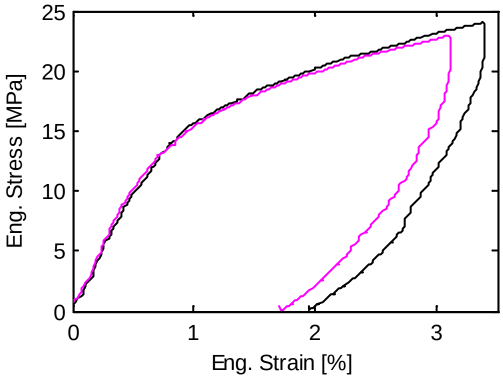

Figure 5: Stress–strain curves under loading-unloading

3 NUMERICAL MODELING

3.1 Finite element model

To simulate the creasing of the paperboard, a two-dimensional finite element model with plane strain conditions was build, which is schematically represented in Fig. 6. At both ends of the system, blank-holders ensured that the laminate was creased appropriately while the punch was moved downwards. The loading of the punch was applied displacement. Symmetry conditions were applied. All tools were considered rigid, whereas the paperboard was equipped with the elastic-plastic material model described in the following Section. The contact between paperboard and tools was assumed frictionless.

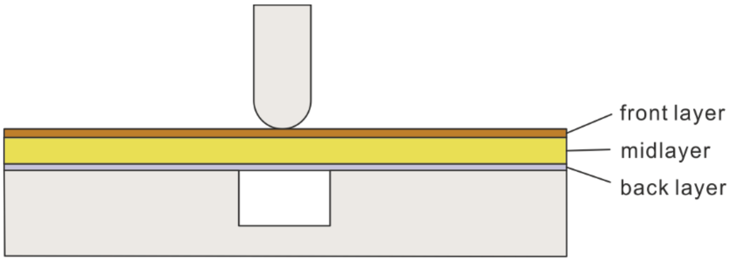

Figure 6: Schematic representation of the finite element model

The finite element analysis was performed with the software package Abaqus. The mesh is shown in Fig. 7.

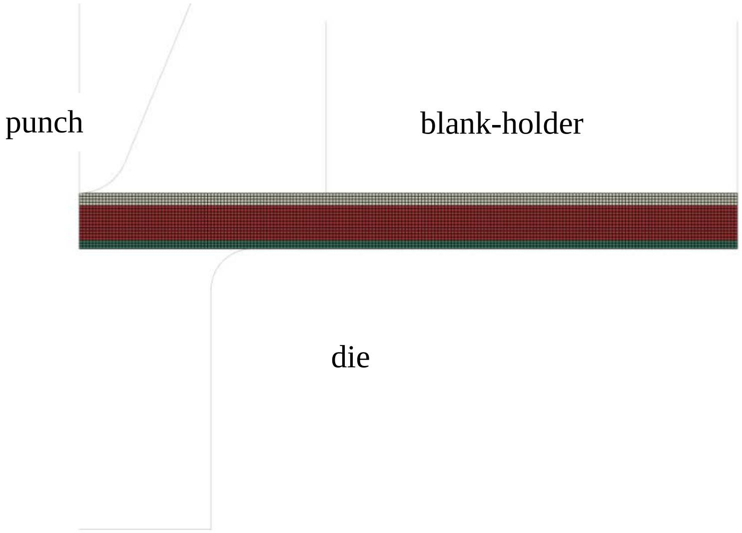

Figure 7: Finite element mesh

To ensure that the applied mesh was converged, a mesh convergence analysis of the creasing model had been performed in terms of force-crease depth relationship. The results of this convergence study can be seen in Fig. 8.

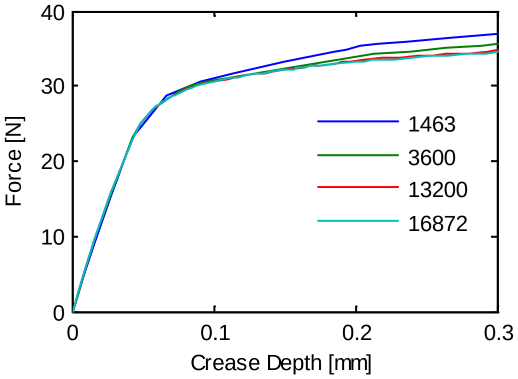

Figure 8: Force-crease depth curves with different element number

3.1 Material model

As discussed previously, the applied material model was elastic-plastic with isotropic strain hardening. While the elastic behavior was linear and orthotropic, the Hill’s 48 yield criterion was used to describe the onset of yield. The post-yield behavior was characterized by the power law hardening function

$$\sigma_y = \sigma_{y0}(1+A\bar{\varepsilon}_p)^m \,, \tag{1}$$

where σ_{y0} denotes the initial reference yield stress, $\bar{\varepsilon}_p$ is the equivalent plastic strain, A and m are dimensionless hardening parameters. These material parameters were calibrated from the stress-strain curves obtained experimentally (see Sect. 2). The resulting in-plane elastic-plastic response matched the tensile tests in MD, CD and 45° well, as illustrated in Fig. 4.

4 VALIDATION

To validate the model, the stress–strain behavior during tensile loading in directions 30° and 60° has been predicted using the parameters calibrated with the MD, CD and 45° data (see Sect. 2). The results have been compared to experimental data, as shown in Fig. 9.

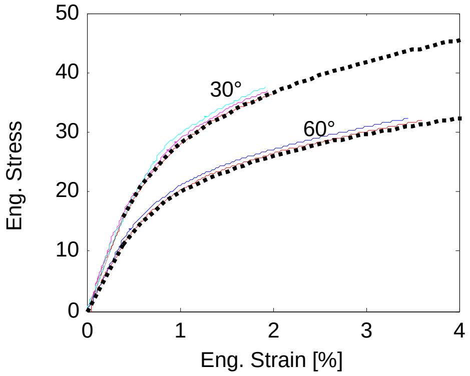

Figure 9: Comparison of experimental (solid) and calculated (dashed) stress-strain curves for uniaxial tension in 30° and 60° directions

Then, the material behavior of the laminated paperboard was computed based on the material properties of the three constituent layers. The resulting stress-strain curves for uniaxial MD and CD tension have been compared to experimental data, as illustrated in Fig. 10.

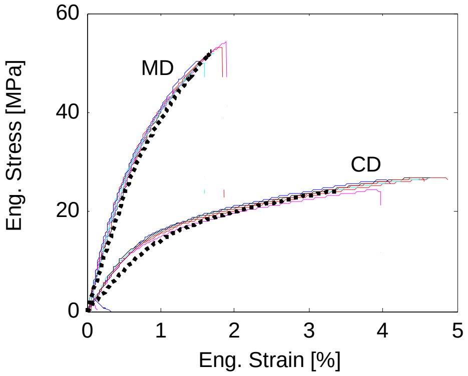

Figure 10: Comparison of experimental (solid) and calculated (dashed) stress-strain curves of paperboard for uniaxial MD and CD tension

As one can see, the numerically obtained curves are slightly below the experimental ones. This can be explained by the behavior of the interface, which has not been taken into account in the simulation.

5 CONCLUSIONS

The creasing of paperboard has a significant influence on the material behavior of the final product. In particular, the potentially occurring delamination plays a crucial role in most applications of packaging products. Thus, investigating the behavior of laminated paperboard during creasing is highly relevant. In this study, the creasing process has been simulated by a two-dimensional finite element model. The material model applied for the separate layers had been characterized and validated by comparison with experimental results. It turns out, that this model is capable of accurately predicting the behavior of the paperboard. In order to further improve the numerical results, the interface properties between the layers and delamination should be taken into account.

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