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Anisotropic elastic-plastic deformation of paper: In-plane model

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ABSTRACT

Laminated paperboard and paper is widely used in packaging products. It generally exhibits highly anisotropic and nonlinear mechanical behavior. The aim of this study is to describe the in-plane material behavior with an orthotropic elastic-plastic model based on the observed experimental behavior. A structural tensor-based approach was applied to model the elastic deformation, while a multi-surface based yield criterion was adopted to describe the yield behavior. The model incorporated nonlinear kinematic and isotropic hardening to capture the anisotropic hardening effect. In the experiment, the compressive yield stress was found to be insensitive to the previous tensile deformation. The proposed model could capture this compression yield stress preserving effect under reverse loading, which in turn reduced the required material parameters as expected. With the material parameters calibrated from a set of simple uniaxial tests in various directions, the model was shown to predict the stress-strain behavior for other orientations satisfactorily. The model was further validated with experiments under complex loading conditions and found to capture the highly anisotropic, elastic-plastic behavior accurately.

1. Introduction

Laminated paperboard is one of the most common packaging materials in industry due to its beneficial characteristics, such as low price, sustainability, and recycling. Depending on the specific requirement, it can be easily designed as a single layer paper or multi-layer sandwich structure. This material exhibits a highly anisotropic mechanical behavior due to its manufacturing process; including anisotropic elasticity, initial yielding, strain hardening, and tensile failure. The principal directions of paper are the machine direction (MD), cross-machine direction (CD) and out-of-plane direction (ZD).

In industry, almost all paperboard packaging includes a creasing operation to obtain a locally deformed zone and a subsequent folding or deep drawing process to form the final box. During creasing, the paperboard is pressed into a channel by a creasing rule to introduce delamination to locally reduce its bending stiffness. In the folding process, the outer layers of paperboard are loaded in-plane tension while the inner layers are in compression. The deformation in deep drawing processes is even more complex, which usually introduces positive longitudinal strain but negative transversal strain (Nakamura et al., 2009). Conclusively, all the operations include a complex loading-unloading-reloading deformation, leading to some common defects such as cracking, buckling, spring-back, and so on. To obtain an accurate prediction of these operations, it is essential to perform studies on two aspects, namely the paperboard anisotropic behavior and the interface delamination between different layers. Since the interface delamination can be described reasonably using a cohesive zone model, the challenge lies in the interface properties characterization. Different methods have been developed to measure the interlaminar strength of paperboard, cf. Fellers et al. (2012), Korin et al. (2007), Li et al. (2016), Nygårds et al. (2007). The other aspect is the mechanical behavior of paperboard and paper, which plays a significant role in the whole process. There are generally two models used to describe the anisotropic mechanical behavior. First, a micromechanical model is often used to predict the overall response by performing analysis on the built fiber network, with its mechanical properties being strongly controlled by fiber-fiber interactions and single fiber properties. Different methods have been developed to generate the artificial fiber network, see e.g. Bosco et al. (2015), Bronkhorst (2003), Kulachenko and Uesaka (2012), Lavrykov et al. (2012), Sliseris et al. (2014). In these models, both fibers and inter-fiber bonds were usually simplified as homogeneous and isotropic continua. Furthermore, the inter-fiber bonds were considered to be either rigid or flexible, which was studied by e.g. Kulachenko and Uesaka (2012), Liu et al. (2011). This kind of network model provides sight into the detailed deformation at the microscale level, but leads to high computational cost.

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The second category of models used to describe the anisotropic mechanical behavior of paper is the more common continuum model. In the literature, several material models have been proposed to describe the elastic-plastic behavior of paperboard and paper. For example, Xia et al. (2002) 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, compression and shear. More recently, Borgqvist et al. (2014) modified this model to take into account the distortional hardening. In this model, an additional set of coupling parameters were introduced to consider the interaction between different sub-surfaces during the hardening evolution. This results in extensive experimental effort to determine these parameters. Tjahjanto et al. (2015) further extended the model to incorporate viscoelastic-viscoplastic effects. This model combined isotropic and kinematic hardening with back-stress terms. For the ease of parameter calibration, the magnitude of the back-stress was defined the same as the hardening resistance of the opposite sub-surface. This treatment provided a reasonable prediction, but required further experimental evidence. Wallmeier et al. (2015) proposed a simple multi-surface yield criterion for the analysis of deep drawing of paperboard. Alternative approaches describe the yield surface based on the Tsai-Wu criterion, see e.g. the model proposed by Harrysson and Ristinmaa (2008). Mäkelä and Östlund (2003) considered the anisotropic behavior by incorporating an isotropic plasticity equivalent transformation tensor. Erkkilä et al. (2015) proposed an in-plane hygro-elasto-plastic model and a hygroexpansivity-shrinkage model that are functions of the dry solids content and fiber orientation anisotropy index. However, in most investigations into the paperboard creasing and folding process, the comparatively simple Hill's yield criterion has been used to describe the onset of yield and also the plastic flow, e.g. in Beex and Peerlings (2012), Huang et al. (2014). Other works dealing with the out-of-plane behavior could be found e.g. in Nygårds (2009), Stenberg (2003). These studies are based on the assumption that the in-plane and out-of-plane problems can be solved independently, which means the in-plane and out-of-plane stress components can only drive the in-plane and out-of-plane inelastic deformation of paper, respectively. Furthermore, several studies have been performed to describe the paper by continuum damage models, such as Isaksson et al. (2006), Tryding et al. (2016), Zechner et al. (2013).

In this work, both tensile and compression tests were first conducted on the paper, with digital image correlation (DIC) system providing information about the axial and lateral strain during tension. Then, a general in-plane elastic-plastic constitutive model was proposed to describe the experimentally observed behavior of paper. The elastic deformation was modeled by adopting the structural tensor concept, while the yield criterion proposed by Xia et al. (2002) was modified to describe the yield surface. The model incorporated nonlinear kinematic and isotropic hardening to capture the anisotropic hardening effect. Further, a straightforward calibration procedure was presented to show the physical meaning of the material parameters in the elastic part and also the internal variables in the plastic part. Finally, with the fitted parameters, a punch test was used to validate the model by comparing the obtained strain fields as well as the punch force-displacement curves.

2. Experimental investigation

2.1. Material characteristics

Paper is in general composed of a network of bonded cellulose fibers. Although the fiber type and manufacturing process of paper varies, its general mechanical behavior remains similar. Paper is classically characterized as an orthotropic material. Its principal directions commonly coincide with the MD, CD and ZD. Due to the manufacturing process, the magnitude of mechanical properties in MD can be 1–5 times higher than that in CD, and up to 100 times higher than that in ZD. In this study, only the in-plane behavior is modeled.

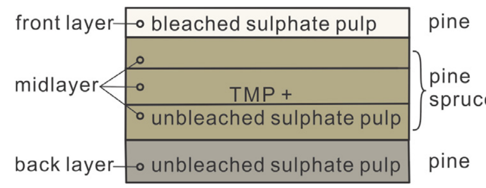

Fig. 1. Schematic of the sample (modified from Li et al., 2016).

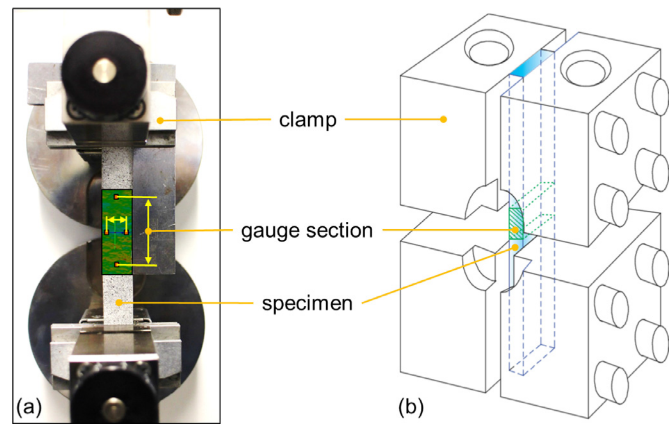

Fig. 2. (a) Tensile test set-up, and (b) assembled Wyoming compression fixture.

The sample under consideration consists of five layers, as shown in Fig. 1. Both top and bottom layer are made from pine wood fibers, whereas the midlayer is a mixture of spruce and pine wood fibers. Since it is very difficult to perform compression on such a thin individual layer, all the tests were conducted on the whole laminated paperboard in this study.

2.2. Experimental methods

To characterize the mechanical behavior of paper, both tensile and compression tests were conducted in different directions. The test samples were cut from a large sheet with a thickness of 0.362 ± 0.007 mm. The shape and dimensions of the tensile test samples followed the standard ISO 1924-2:2008 (International Organization for Standardization, 2008a). The tensile test setup included a Zwick Z5 testing machine and an ARAMIS 4M digital image correlation (DIC) system, which provided accurate non-tactile displacement and strain measurements at the surface of the specimen during the test procedure, as shown in Fig. 2(a). For the uniaxial deformation state, only two points along the longitudinal direction of the specimen were needed to determine the strain values. In addition, another two points in the transversal direction were simultaneously recorded to generate the Poisson's ratio. It should be noted that the initial distance between the two points in each direction was big enough to achieve a smeared global value. Additionally, the tensile test was displacement controlled with a loading speed of 5 mm/min.

Due to the relatively small thickness of paper, measures must be taken to avoid buckling in compression tests. In industry, the short span compression test (SCT) is most commonly used to measure paper compression strength, but the influence of the clamps prevents the capturing of the stress-strain curves (International Organization for Standardization, 2008b). Therefore, the long span compression test (LCT), which includes lateral supports to prevent