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A plasticity model for predicting the rheological behavior of paperboard

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ABSTRACT

The sorption of water into the paperboard exposes a container to reversible and irreversible deformations under relative humidity variations. In this study, an elasto-plastic material model is used to demonstrate how through-thickness dry solids content gradients can generate permanent in-plane strains in paperboard. The measurements presented in this paper indicate that in consecutive loading-unloading cycles, the yield stress either remains roughly constant or decreases, and an additional permanent set of strain is obtained even when the maximum tension of repetitions stays constant. Two modified approaches concerning elasto-plastic hardening behavior based on the measurements of this work and the observations of previous studies are introduced. The simulated results exhibit some shared features of the frequently observed shrinkage behavior of paperboard exposed to cyclic relative humidity changes. The results suggest that with the use of a suitable hardening approach, the plastic deformations arising from through-thickness dry solids content gradients may be considered as a time-independent component for simulations of phenomena such as moisture-accelerated creep and release of dried-in stresses.

1. Introduction

The rheological behavior of paperboard is connected to phenomena such as stress relaxation (Craven, 1962), strain recovery and moisture-accelerated creep. All these are important factors affecting paperboard production, converting and end-use quality. The potential of paperboard-based packages to resist a buckling collapse under a compressive load in relative humidity (RH) fluctuations during long-term storage or shipping is an important aspect of the performance of corrugated containers.

The sorption of water into the paperboard exposes the container to hygroexpansion and changes in mechanical properties and internal stresses. Depending on the drying history, the deformations arising under cyclic RH conditions may manifest irreversible behavior (Uesaka et al., 1992; Nanri and Uesaka, 1993). Long compressive loading times increase the risk for collapse due to creep. Moisture-accelerated creep, also known as mechano-sorptive creep, is a phenomenon in which the cyclic dry solids content (DSC = kg dry solids/(kg dry solids + kg water)× 100%) changes increase the creep rate in paperboard. This creep rate increases with lower DSC levels, and because of the cyclic DSC changes, the creep rate is usually even higher than it would be at any constant DSC level (Byrd and Koning, 1978; Leake and Wojcik, 1992; Coffin, 2005). Delayed recovery is also a rheological property of paperboard. Elastic recovery immediately follows the stress-strain cycle, but after this, the strain continues to decrease under zero-loading conditions as a delayed strain recovery (Gates and Kenworthy, 1963; Skowronski and Robertson, 1986).

Orthotropic elasto-plastic approaches to predict the in-plane tensile response and deformation of paper have been applied by Castro and Ostoja-Starzewski (2003); Mäkelä and Östlund (2003) and Xia et al. (2002). The effect of pre-straining on the yield surface has been modeled by Borgqvist et al. (2014). The behavior of paperboard and corrugated cardboard under cyclic loading has been studied by Allaoui et al. (2009). The effect of local material variations on out-of-plane deformations has been studied by Lipponen et al. (2008b) and Erkkilä et al. (2015). Hygroviscoelastic models for predicting history-dependent dimensional stability and hygroexpansivity have been introduced by Uesaka et al. (1989) and Lif (2006). A model capturing several phenomena has been presented by Coffin (2009) and the effect of pre-straining on the tensile response of paper by using an efficiency factor has been studied in Coffin (2012). For decades, several macro- and micro-

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scale explanations have been proposed to describe the phenomena related to moisture-accelerated creep. (Habeger and Coffin, 2000) have considered the effect of DSC gradients and the related through-thickness stress distributions on the moisture-accelerated creep. The effect of hygroexpansion on creep behavior has also been considered by Urbanik (1995) and Haslach et al. (1994). Alfthan et al. (2002) and Alfthan (2003) have demonstrated that nonlinear creep behavior of the material combined with the moisture gradients occurring during DSC changes and the potential material inhomogeneities may cause stresses inducing the moisture-accelerated creep. Samples of very low basis weight was used by Alfthan (2004) to minimize the effect of through-thickness DSC gradients. A micro-scale modeling approach has also been used by Strömbro and Gudmundson (2008a) and Strömbro and Gudmundson (2008b) to investigate the effects of different parameters on the moisture-accelerated creep. (Vlahinić et al., 2012) have suggested that the viscous softening and both the basic and moisture-accelerated creep are mainly originating from the nanoscale movement of water which enhances the internal lubrication. (Padanyi, 1993) has proposed that aging is a parameter as important as temperature and relative humidity for creep and in Padanyi (1991) has been concluded that physical aging and mechano-sorptive effects are actually the same phenomenon. In Reichel and Kaliske (2015a) and Reichel and Kaliske (2015b) a 3D model for wooden structures demonstrating linear viscoelastic and non-linear viscoelastic-viscoplastic material behavior have been presented. The accumulated mechano-sorptive deformations were considered as amplification of mechanically induced creep.

The purpose of the present study is to estimate the potential of time-independent elasto-plastic hardening simulations to generate permanent deformations arising from the through-thickness DSC gradients. The basic concept is same as in the simple theoretical two bar model presented by Selway and Kirkpatrick (1992). The theoretical approach is extended by a material model describing the elasto-plastic behavior of paperboard. In addition to the traditional approach, the hardening behavior arising from DSC cycling is dealt with using two modified approaches based on observations in Östlund et al. (2004) and Nanri and Uesaka (1993) and the measurements introduced in this work. The results of the simulations are discussed with reference to previously published results related to the moisture-accelerated creep and the internal stresses. The results suggest that the accumulation of the plastic strains may have significant role in the phenomena arising in cyclic humidity conditions. The simulations also address the importance of the hardening behavior under cyclic loadings.

2. Measurements

The tensile behavior in the cross-machine direction (CD) (see Fig. 1) of an unbleached semi-chemical board sample with a basis weight of 175 g/m^2 and a thickness of 257 µm was measured in a standard test atmosphere of 23 °C/50% relative humidity (RH). The test procedure consisted of three repetitions of loading-unloading tests, named 1, 2 and 3 accordingly (see Fig. 2 and Table 1). The test samples were initially conditioned at 50% RH. Between the repetitions of the load-unload tests, the board samples were conditioned to 35% and 98% RH levels in a climate chamber (Memmert Climatic CTC 246 MEMMCTC256) that produced changing RH as described in Table 1. The temperature was 23 °C. The relative humidity target levels were chosen according to the climate chamber's user manual in a manner that the levels were in a safe operating region. There were also reference samples which were conditioned at constant 50% RH and 23 °C in the test laboratory for the same time period as that of the samples conditioned in the climate chamber. Tensile tests were performed using a commercial Lloyd Instruments tensile tester equipped with a 100 N (in the preliminary test 1 kN for the MD) load cell. The span length and width of the samples were 180 mm and 15 mm, respectively. The elongation speed was 1 mm/s.

In the preliminary tests, the MD (machine direction) and CD (cross-machine direction) samples were strained until rupture, using a constant elongation speed of 1 mm/s. The flute direction of the corrugated board, which typically carries the main top-load of stacked boxes, is along the CD. Also, the non-linear load-elongation region is more prominent in the CD. Due to those aspects, the CD samples were selected for cyclic tests. The target tension of 6500 N/m (point A in Fig. 2) was fixed according to the preliminary test results of the CD samples.

Examples of the measured curves describing the typical tension-strain behavior are presented in Fig. 3. In the measure-

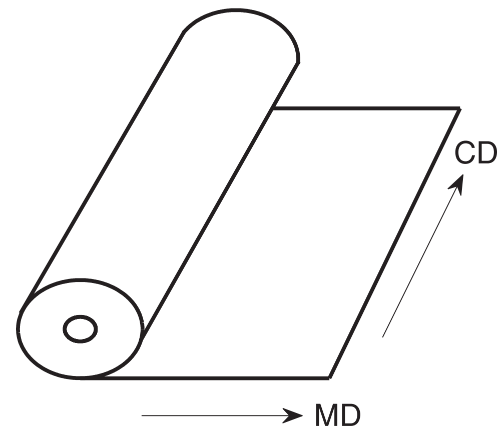

Fig. 1. The in-plane directions of paperboard. MD and CD stand for machine and cross-machine direction, respectively.

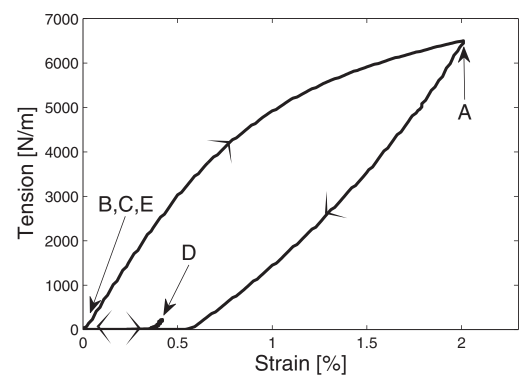

Fig. 2. One tensile test. The sample is loaded to the target tension of 6500 N/m (B → A); unloading to the initial start position of the tensile test (A → C); a 30 s pause (C); loading to 200 N/m tension (C → D); and unloading to the initial start position of the tensile test (D → E).

Table 1
The cyclic tensile test procedure for cyclic relative humidity (RH) conditioned samples and reference samples.

Operation: cyclic RH cond. sample Tensile test 1	Time	Operation:ref. sample Tensile test 1
From 50% RH to 35% RH	6 h	at 50% RH
From 35% RH to 98% RH	16 h	at 50% RH
From 98% RH to 50% RH	6 h	at 50% RH
Tensile test 2		Tensile test 2
at 50% RH	16 h	at 50% RH
From 50% RH to 35% RH	6 h	at 50% RH
From 35% RH to 98% RH	16 h	at 50% RH
From 98% RH to 50% RH	6 h	at 50% RH
Tensile test 3		Tensile test 3