Mechanics of Materials 91 (2015) 76–94

Contents lists available at ScienceDirect

Mechanics of Materials

journal homepage: www.elsevier.com/locate/mechmat

Explaining irreversible hygroscopic strains in paper: a multi-scale modelling study on the role of fibre activation and micro-compressions

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ARTICLE INFO

Article history:
Received 3 March 2015
Received in revised form 8 June 2015
Available online 26 July 2015

Keywords:
Fibrous material
Meso-structural model
Multi-scale
Hygro-expansivity
Irreversibility
Local buckling

ABSTRACT

This paper proposes a meso-structural model for the discrete fibrous network of paper, which is able to upscale the irreversible phenomena from the underlying hygro-mechanics towards the effective behaviour at the macro-scale. The swelling of individual fibres, induced by moisture content variations, is transmitted to the network through inter-fibre bonds and governs the resulting effective material response. The present approach is based on a recently developed discrete meso-structural model for the reversible part of the response, which distinguishes between the influence on the hygroscopic behaviour of free-standing fibre segments and inter-fibre bonds. The network structure, fibre and bond geometries and hygro-elastic properties are explicitly incorporated. The major novelty of this contribution is the extended fibre constitutive model, enabling to describe some typical irreversible mechanisms and instability effects related to the history of the manufacturing. This extension strongly affects the effective material behaviour beyond the elastic range. Despite the valuable work in the literature, no papers can be found dedicated to meso-structural models including these phenomena. Using an appropriate homogenization strategy, the unit-cell is solved analytically, capturing irreversible shrinkage in restrained dried paper and the occurrence of local buckling within the bond for freely dried material. The proposed scale transition offers a deeper insight into the complex relation between the events occurring at the different length scales. The potential of the proposed methodology is demonstrated through the convincing agreement with experimental data obtained from the literature.

1. Introduction

Paper is a composite material mainly composed of cellulose fibres organized in a discrete network structure (Niskanen, 1998). Paper based materials are extremely sensitive to moisture content variations, involving dimensional changes at different length scales. The strongly anisotropic moisture induced deformation exhibited by a single fibre is transferred to the meso-scale network through the interactions occurring in the inter-fibre bonds due to the competition of hygroscopic and mechanical strains in the overlapping fibres. These moisture related phenomena in the underlying fibrous network collectively define the effective hygro-expansive response at the sheet level, which is generally manifested through complex

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http://dx.doi.org/10.1016/j.mechmat.2015.07.009
0167-6636/

in-plane and especially out-of-plane deformations. Moreover, the effective paper behaviour is strongly influenced by the drying conditions during the manufacturing process, where paper may be subjected to web tension during drying. This induces internal stresses (and strains) that can be released when paper is subsequently moistened for the first time. The release of dried-in strains induces an irreversible shrinkage of the restrained dried paper sheet, see Fig. 1(a). After the first moisture cycle, a linear reversible response is generally retrieved. A significantly different behaviour occurs if no load is applied during the drying stage. For freely dried paper, a linear relation between hygro-expansive strain and moisture content is observed without any irreversible deformation, as shown in Fig. 1(b). The hygro-expansive coefficient, which indicates the proportionality ratio between the reversible strain variation and the moisture content variation, is smaller for restrained dried paper than for freely dried paper (Nanri and Uesaka, 1993; Larsson and Wagberg, 2008).

The hygro-expansive behaviour of paper is governed by a cascade of events involving different length scales, which makes the understanding of the problem extremely complex. A wide range of underlying mechanisms possibly contributing to the effective response has been suggested; however, it is yet unclear whether they can quantitatively resolve the sheet level observations. A thorough understanding of the moisture associated phenomena affecting paper dimensional stability in relation to the fibre and network behaviour and the development of consistent predictive models based on the micro- and meso-structural features constitute a major scientific challenge.

Discrete meso-structural models are a natural choice to describe the underlying paper fibrous network. These kinds of descriptions, in fact, allow to incorporate the behaviour of single fibres and their contribution as individual constituents in the discrete network, in order to determine its macroscopic equivalent continuum response. In the literature, paper is often described through stochastic analytical or computational network models (Cox, 1952; Ostoja-Starzewski, 1998; Stahl and Cramer, 1998; Ostoja-Starzewski and Stahl, 2000; Bronkhorst, 2003; Ramasubramanian and Wang, 2007; Strömbro and Gudmundson, 2008a,b; Liu et al., 2010, 2011; Kulachenko and Uesaka, 2012; Sellén and Isaksson, 2014). Individual paper fibres are generally represented as chains of trusses (e.g. in Cox, 1952; Ramasubramanian and Wang, 2007) or beams (e.g. in Bronkhorst, 2003; Ostoja-Starzewski and Stahl, 2000; Liu et al., 2010, 2011), commonly characterized by their axial properties only. Inter-fibre bonds are the points of connection of these elements and they usually coincide with the nodes. Different constitutive models for the fibrous network have been adopted (e.g. elastic Cox, 1952; Ostoja-Starzewski and Stahl, 2000 or visco-elastic Strömbro and Gudmundson, 2008a,b; or elasto-plastic Bronkhorst, 2003; Ramasubramanian and Wang, 2007; Liu et al., 2011), all of them providing good estimations of the effective behaviour in the range of interest. While most of the models are focussed on the mechanical response only, some hygroscopic effects are also addressed. In Strömbro and Gudmundson (2008a,b) and Sellén and Isaksson (2014), mainly discussing their relation with accelerated creep.

A specific analysis at the meso-structural level of the phenomena determining paper's reversible hygro-expansive behaviour is presented in Uesaka (1994). The author emphasizes the important role played in the effective material response by the interaction of hygroscopic and mechanical properties within the bonding area. The proposed theory qualitatively explains a collection of experimental results (Uesaka, 1994; Uesaka and Qi, 1994). However, a quantitative expression of the hygro-expansive coefficients for a fibrous network of given geometry and hygro-mechanical properties is herewith not within reach. Moreover, the influence of the production process on the resulting material response is not explicitly incorporated. To the best of our knowledge, the literature seems to lack models founded on a fibre and network level, especially dedicated to the prediction of paper hygro-mechanics.

This paper is focussed precisely on the micro-structural origin of the irreversible part of the hygroscopic response. To this end, the model presented in a previous work (Bosco et al., 2015a) is extended including an enriched constitutive theory for the paper fibres. The proposed constitutive assumptions are based on the investigation of the underlying physical mechanisms, assumed responsible

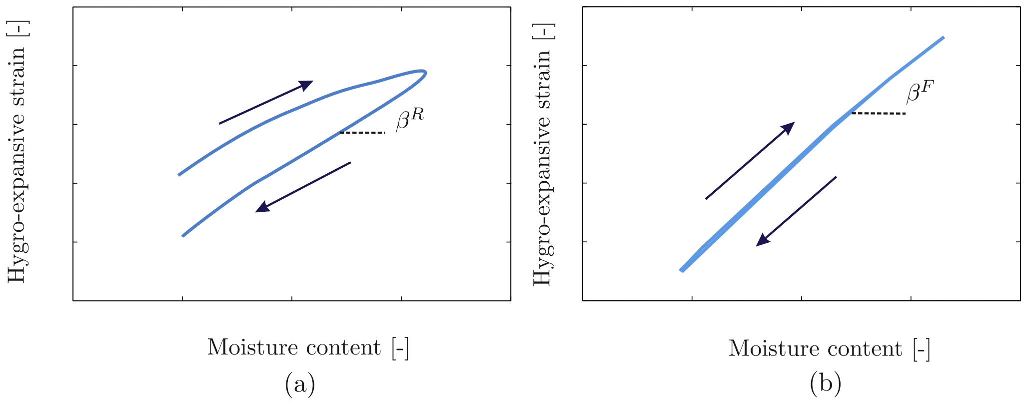

Fig. 1. Qualitative trend of the hygro-expansive strain as a function of moisture content for (a) restrained dried and (b) freely dried isotropic paper hand sheets.