MULTISCALE MODELING OF THE HYGRO-MECHANICAL RESPONSE OF PAPER SHEETS

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PROEFSCHRIFT

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door

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geboren te Bhubaneswar, India

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Logic will get you from A to B. Imagination will take you everywhere.

— Albert Einstein

SUMMARY

Paper sheets reveal pronounced changes in shape and dimensions upon exposure to variations in moisture, which comprises digital printing operations. These are observed in the form of curls, waviness and buckling at the sheet-scale of paper. In digital printing, this undesired behavior is due to the fact that the moisture is rapidly absorbed in paper and thereafter evaporated within a short period of time.

These dimensional changes originate from the single fibre level, which affects the fibre network through the inter-fibre bonds (regions where the fibres overlap). At these bonds, an interaction of the hygroscopic and mechanical response of the fibres occurs, entailing micro-stresses and associated sheet-scale deformations. In order to understand this macro-scale behavior of paper, it is essential to study the complex fibrous network at the micro-scale.

In Chapter 2, a level-set based XFEM approach is used to model the hygro-elastic response of complex fibrous networks in a two dimensional framework. The fibres are assumed to be completely bonded in the inter-fibre bonds. The fibre edges are described by the zero level-set of a higher dimensional function. The level-set method coupled with X-FEM captures the geometrical description of the fibres adequately with a lower system size, since the discretization is decoupled from the geometry. Therefore, LS-XFEM formalism is shown to be successful in modeling the hygo-mechanical response of complex networks of fibres.

During the manufacturing process of paper, when the pulp is dried under restraint, internal stresses/strains are developed as explained by the fibre segment activation mechanism. Upon exposure to a moisture cycle (e.g. during printing), these strains are released at the fibre level which induces permanent deformations at the macro-scale accompanied by dimensional instabilities. To capture such phenomena, a rate-independent kinematic hardening plasticity model is developed for the individual fibres in Chapter 3. The results obtained from the numerical network simulations using this model illustrate the influence of microstructural properties of the network (e.g. the fraction of free-standing fibres versus bonded fibres) on the macroscopic irreversible strains.

In addition to printing, the moisture infiltration in paper occurs also via the environment. Under sustained loading over a period of time, creep takes place in paper networks. These macroscopic deformations observable in paper networks over time are of great interest due to the lack of a suitable model that explains this behavior. Furthermore, this intrinsic time-dependence is of significant importance for the service conditions of paper packaging products. In order to understand the effects of time scales on the dimensional alterations in paper, a rate-dependent plasticity model based on a power law is adopted in Chapter 4. The model parameters are identified from experimental results performed on single paper fibres (Jentzen [32] and Sedlachek [64]). Thereafter, network simulations are performed, which demonstrate the time dependence at the sheet level.

In order to understand the role of the degree of bonding between the fibres in bonded regions on the sheet-scale response of the network, the assumption in Chapters 2, 3 and 4 of a full kinematic constraint between fibres at the bonds is partially relaxed in Chapter 5. In the relaxed bond model, the fibres in bonds can have independent displacements, whereby the displacement difference is governed by interfacial

stiffness. This is modeled numerically by embedded interfacial elements that connect the fibres in the bonded regions of network. The computational results reveal the influence of the kinematic constraints in the bonds at the sheet-level behavior of the network in addition to the anisotropic response of the network.

With the research undertaken in this thesis, it has been made possible to capture the complex geometry of paper networks adequately, enabling the prediction of their hygro-expansive response. A clear understanding has been achieved on the role of various network parameters in determining the hygro-mechanical behavior of paper. The developed numerical models allowed to gain insight into the hygro-mechanical response of paper fibres and can be further developed to model macro-level properties of paper.

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