Simboard

Improved process stability in three-dimensional paper forming through numerical mapping of material inhomogeneity

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Abstract
In this project, the inhomogeneous material structure of fiber-based materials was investigated in detail, with a focus on the macroscopic numerical representation of local thickness, density and fiber orientation. The regions of significant inhomogeneity were identified and measured using a transmitted light method. The stochastic properties of the paper structure were approximated and represented by mathematical models to map the structure distribution. In addition, a method was developed to integrate the local structure into numerical simulation programs and implemented in 3D forming processes such as deep drawing and hydroforming.

Project description
The prediction of forming processes is subject to increasing uncertainty when the microstructure varies significantly from the macrostructure. This leads to fluctuations in material behavior, which is particularly important for numerical modeling of paper in finite element simulations. The inhomogeneous distribution of properties such as density, thickness and fiber orientation due to factors such as refining level, fiber distribution, fiber composition and process conditions leads to stochastic material properties. Therefore, it is essential to consider the effects of material inhomogeneity on characterization and forming processes. The aim of this project is a detailed analysis of the local material structure as well as the numerical representation of stochastic structures and their influence on the material behavior. As a result, approaches for process and tool design will be developed and target values for paper production and characterization will be derived to improve process stability.

The objectives of the project are

- Material structure characterization: Identification and characterization of the relevant inhomogeneity state of the paper to gain a comprehensive understanding of the material structure.
- Numerical modeling with inhomogeneities: Development of a numerical model that represents the material behavior taking into account inhomogeneous distributions of the material data and allows realistic simulation of forming processes.
- Optimization and validation of forming processes: Development of approaches to improve the reliability of paper forming processes by varying material and process parameters while taking into account inhomogeneous material properties. The method will then be validated on selected processes and materials.

Results
The first step is to determine the local property distribution using non-destructive methods. The local basis weight, thickness and fiber orientation distribution can be easily and quickly determined by high-resolution transmitted light and gray scale measurements. For the first two parameters, the correlation with β-radiation and the profilometer was confirmed; for the fiber orientation, directional detection was performed based on image processing. The mathematical models derived from the measurement data to map the structure distribution allowed the stochastic properties of the material to be captured and incorporated into the simulation programs.

The second step is material characterization and modeling. First, an elastic-plastic, orthotropic material model was developed to describe the behavior of paper in the plane. The uniaxial tensile test in three directions (MD, 45° and CD) and the compression test in the thickness direction in combination with empirical formulas can be used to model the material anisotropy based on Hill. The out-of-plane delamination behavior is then developed. To study deformation and delamination in the thickness direction, compression, shear, and tensile tests in the thickness direction are required to determine Young‘s modulus, shear modulus, and delamination parameters. To model the delamination behavior, an interface model is used where cohesive elements with zero thickness and a traction-separation description or a cohesive interaction are used for the adhesive interfaces.

The combination of the local physical properties with the already established material model allows the simulation of inhomogeneities. Figure [1] shows the procedure for the numerical representation of inhomogeneities with the stochastic FEM and the implementation in the tensile test.

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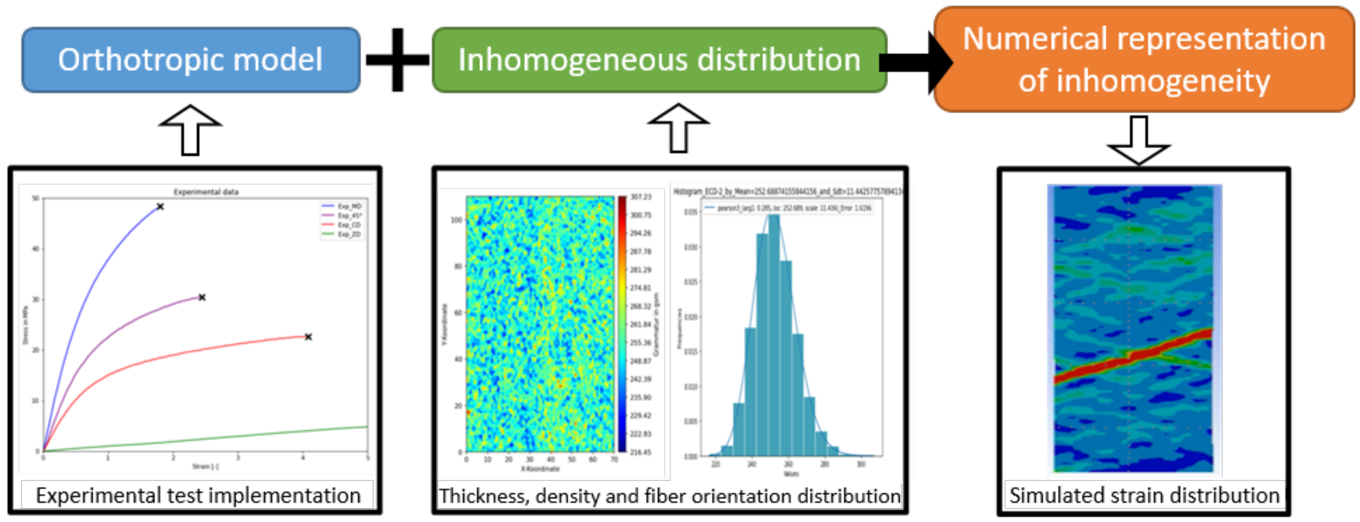


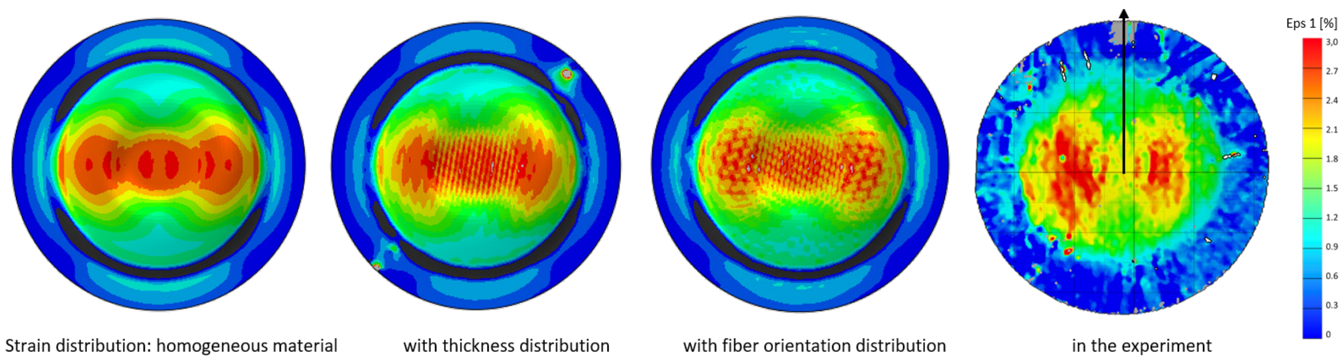
[1] Procedure for modeling inhomogeneous materials

The results of the numerical investigations have shown that materials with locally highly pronounced inhomogeneous properties tend to exhibit locally high strains and thus premature failure. This suggests that the homogeneity of the material structure has a significant influence on the mechanical behavior and elongation at fracture of the material. The detailed analysis and modeling of the inhomogeneous structure provided further insight into the failure of materials and the relationships between material structure and mechanical behavior.

The developed material models are used to simulate process models for 3D forming processes using conventional (deep drawing) and active media (hydroforming) forming processes. For the deep drawing process, an automated wrinkle detection method was developed in order to quickly and quantitatively compare experimental results. An experimental and numerical parameter study has shown that increasing the blank holder force and the drawing gap leads to an increase in the number of wrinkles, while increasing the coefficient of friction leads to a reduction in the number of wrinkles. In contrast, punch speed and draw depth have no significant effect on the number of wrinkles.

In hydroforming, increasing the forming pressure up to a certain limit results in greater deformation without damage. At constant pressure, an increase and then a decrease in deformation was observed with increasing hold-down force. This indicates that there is an optimum hold-down force for a given material and forming pressure. Decreasing the friction coefficient slightly increases the formability of the paper. Figure [2] shows the main deformation distribution of the homogeneous material in the simulation, the material with thickness and fiber orientation distribution, and a comparison with the experimental results. Although there is some measurement noise, the inhomogeneity of the material itself should not be ignored. With the help of stochastic FEM, the results of the forming process can be predicted more accurately.

The results of the project allow a deeper understanding of material characterization and forming processes taking into account the inhomogeneity of paper. In particular, the developed numerical model has the potential to improve the reliability of the paper forming process and to expand the application areas of paper forming.



[1] Comparison of the inhomogeneous strain distribution in the simulation with the homogeneous distribution and the result of hydroforming

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