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Multi-scale modelling of building materials and its experimental validation

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Abstract: In this work, multi-scale models for wood, asphalt concrete, and cementitious materials are presented. Leading, on the one hand, to a better understanding of the complex behaviour of these materials and, on the other hand, providing accurate sets of macroscopic properties as input for structural simulation tools. In the following, the key feature of each multi-scale approach is briefly outlined and the link to a structural application is indicated. In order to derive a proper understanding of the material behaviour, to identify material parameters, and to validate the obtained material models at various length scales, experimental investigations are obligatory and an integral part of each presented model.

Keywords: continuum micro-mechanics; wood; asphalt; concrete

1. Introduction

The requirements for building structures and building elements, respectively, in civil engineering are increasing constantly, for different reasons. Whether the timber industry needs to improve their building products to gain market share, the performance demands on asphalt pavement structures rise due to increasing heavy-load traffic, or better prediction tools of the fire resistance of tunnel structures are requested because of recent accidents.

In all cases, more accurate material models and advanced simulation tools are needed for improved design of such sophisticated structures. Moreover, the variability of the material properties has to be understood and suitably described in order to prevent exaggerated safety factors, resulting in an uneconomic over-dimensioning of building elements. Such an understanding and an appropriate resolution of the origin of the observed material behaviour require insight into the microstructural processes of these materials. For this reason, multi-scale models for different building materials have been developed at the Institute for Mechanics of Materials and Structures, allowing us to relate the material properties at the structural scale (macro-scale) to finer-scale characteristics such as material composition and behaviour of the constituents. Recent developments in finer-scale characterization of materials, on the one hand, and micromechanics, on the other hand, provide the basis for the formulation of material models incorporating several scales of observation. The link between microstructural and macroscopic characteristics can be established by means of homogenization techniques within the framework of continuum micromechanics [1].

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In this work, multi-scale models for wood, asphalt concrete, and cementitious materials are presented. Leading, on the one hand, to a better understanding of the complex behaviour of these materials and, on the other hand, providing accurate sets of macroscopic properties as input for structural simulation tools. In the following, the key feature of each multi-scale approach is briefly outlined and the link to a structural application is indicated.

The complex microstructure of wood leads to a highly diversified failure behaviour at the macroscale. Nevertheless, many of the macroscopically observed failure modes can be traced back to one and the same microscale failure mechanism. Shear failure of lignin (main matrix component of wood) is one such microscale failure mode, which can be described with a von Mises-criterion. By approximating strength-governing strain peaks in lignin by quadratic strain averages, and application of an appropriate upscaling scheme [2], micromechanically-based estimates for elastic limit states of wood are finally obtained. This information about the strength behaviour is then used as input for numerical tools, aiming at better understanding and optimization of different wood-based products. Herein, a numerical simulation tool, which is able to predict the bending strength of timber elements depending on the number and arrangement of knots, will be presented.

For asphalt concrete, the viscoelastic behaviour of bitumen is identified with nanoindentation tests at a microscopic scale. Via upscaling in the Laplace-Carson space, using different homogenization schemes at different length scales, the multi-scale model provides access to the viscous properties of asphalt concrete as a function of the mix design [3]. These macroscopic properties serve as input for a numerical tool assessing the performance of flexible pavements. Results obtained from applications of this analysis tool to pavements subjected to combined thermal and traffic loading will be presented.

Considering cementitious materials, a micromechanical explanation for the hydration degree-strength relationships of cement pastes and mortars, covering a large range of compositions, will be given. Thereby, the overall stresses acting on cement pastes and mortars are related to higher-order deviatoric stress averages in needle-shaped hydrates. When the latter stresses reach a critical strength value, the overall stresses refer to the (quasi-brittle) macroscopic compressive strength of cementitious materials. In this context, a single deviatoric hydrate strength can explain the compressive strengths of cement pastes as a function of the hydration degree, over a wide range of water-cement ratios [4].

In order to derive a proper understanding of the material behaviour, to identify material parameters, and to validate the obtained material models at various length scales, experimental investigations are obligatory and an integral part of each presented model above.

Finally, the developed modelling strategies will show, that only a dual approach, combining micromechanical models with powerful numerical algorithms for simulations at structural scale and, thus, spanning all relevant length scales from nanometers to meters, provides the necessary strong base for modern design and enables to meet the different demands on building products and structures mentioned at the beginning.

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