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Multi-scale computational homogenization

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Introduction
Most of the materials produced and utilized in industry are heterogeneous on one or another spatial scale. The adequate modelling of manufacturing processes and the product performance requires the solution of a multi-scale problem.

Figure 1 Examples of metallic heterogeneous microstructures.

☐ The aim is to develop a computational homogenization technique for the multi-scale modelling of non-linear deformation processes of multi-phase materials.

Computational homogenization
Computational homogenization is based on the solution of two nested boundary value problems, one for the macroscopic and one the microscopic scale. Thus, the stress-strain response at a macroscopic material point is obtained from the behaviour of the underlying microstructure.

First-order
☐ The classical first-order computation scheme [1], see Fig. 2, fits entirely in a standard local continuum mechanics framework.
☐ Valuable tool in retrieving the macroscopic mechanical response of non-linear multi-phase materials.
☐ However, the applicability is generally restricted to cases where the characteristic size of the material microstructure is negligible with respect to the spatial variations of the macroscopic deformation field.

Second-order
In order to deal with the limitations, a novel second-order computational homogenization procedure leading to a higher-order continuum on the macrolevel has been proposed [2], see Fig. 2.

☐ The relevant microstructural length scale is directly incorporated into the description on the macrolevel.
☐ This approach allows to describe certain phenomena that cannot be addressed by the first-order scheme, such as (geometrical) size effects, macroscopic localization and surface layer effects.

Examples

Macroscopic localization
Tension of a voided plate (as a heterogeneous configuration) with a material imperfection, which triggers the development of a localization band, is analyzed using the first-order and the second-order computational homogenization scheme.

Figure 3 The first-order computational homogenization analysis results in a mesh dependent strain distribution (a) and (b). The second-order scheme leads to a localization band, which is independent of the mesh size (c) and (d).

Boundary shear layer
Simple shear of a thin heterogeneous strip is considered. The constraints on the top and bottom surfaces are modelled using higher-order boundary conditions (zero shear strain).

Figure 4 Shear distribution along the height of the strip (left) and overall shear stress-strain response (right) for several ratios of the strip thickness $H$ to the microstructural length scale $d$. Boundary layers with a vanishing shear are clearly observed (left), giving rise to a size effect (right).

Figure 5 Microstructural deformation patterns in the sheared macroscopic thin layer for $H/d = 5$ (left) and $H/d = 50$ (right).

Conclusions
Computational homogenization provides a versatile strategy to establish micro-macro structure-property relations based on the behaviour of multi-phase microstructures.

References: