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TITLE: **Fundamental investigation of mesoscale modelling of carbon fibre bundles in sheet moulding compounds (SMC)**

AUTHORS: **Olma, Marcel[a*]; Krauß Constantin[a]; Schreyer, Louis[a]; Wittemann, Florian[a]; Kärger, Luise[a];**

AFFILIATIONS: [a] **Karlsruhe Institute of Technology (KIT), Institute of Vehicle System Technology Lightweight Engineering, Karlsruhe, Germany, *email: marcel.olma@kit.edu**

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Carbon fibre-reinforced sheet moulding compounds (C-SMC) are used in structural components for the automotive and aerospace industries due to their weight-specific properties [1- 3]. To support component development and ensure robust manufacturing, a broad range of process-simulation approaches for SMC has been established. Macroscopic approaches range from historic-classical Hele-Shaw models that treat the material as a single-phase medium [4] over more advanced formulations based on the fibre orientation tensor framework by Advani and Tucker [5] up to modern rate-dependent plasticity models [6]. While these macro-scale methods provide valuable insight, they cannot resolve the mesoscale mechanics of individual fibre bundles, which may play a critical role in C-SMC flow behaviour and final fibre architecture. Meyer et al. [6, 7] developed a Direct Bundle Simulation (DBS) model for glass-fibre SMC (G-SMC), which describes glass fibre bundles as chains of truss elements.

In the present work, the DBS concept has been adapted to C-SMC to capture the differences in bundle geometry and deformation behaviour: Glass-fibre bundles are typically long and slender with a small, roughly circular cross section, whereas carbon-fibre bundles exhibit a rectangular cross-section with a considerably higher aspect ratio. Operating at the mesoscale, the carbon-fibre DBS model is thus constructed to resolve individual carbon-fibre bundles as paired parallel sub-bundles, each represented as an array of 1D truss elements shown in Figure 1. These sub-bundles interact via hydrodynamic forces with the surrounding matrix, enabling concurrent simulation of mesoscale resin flow and fibre-bundle kinematics via two-way coupling. This approach also makes it possible to split the carbon-fibre bundles as visible in real components.

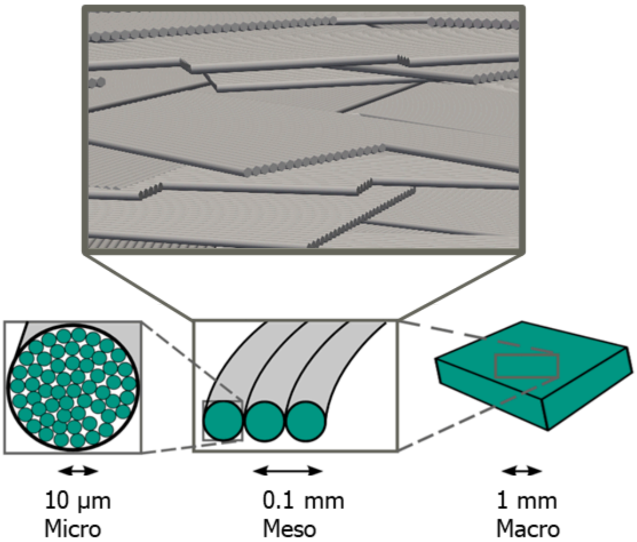

Figure 1: Schematic representation of the different length scales in process simulations (micro, meso, and macro) by showing the respective sizes and modelled carbon fibre bundles before compression moulding in Abaqus2021 .

Because the C-SMC material may undergo significant thickness, the process simulation must accurately represent the resulting large deformations. Therefore, a Coupled Eulerian–Lagrangian (CEL) formulation based on the Arbitrary Lagrangian–Eulerian (ALE) method, implemented in Abaqus/Explicit 2021 (Hf14), is employed [9]. In CEL, the Eulerian domain forms a fixed mesh covering the complete mould cavity. Material occupies non-void cells and undergoes a Lagrangian step in which material points move with the instantaneous velocity field. Subsequently, the deformed material configuration is consistently re-mapped onto the stationary Eulerian mesh, allowing both large deformations and accurate interface tracking.

Using the example of the squeeze flow behaviour of a rectangular sample, the fundamental mechanisms that govern C-SMC compression moulding are investigated to evaluate the evolution of carbon-fibre bundle structures. The model consists of two flat discrete rigid tools, where the lower tool is fixed in space while the upper tool moves shown in Figure 2.

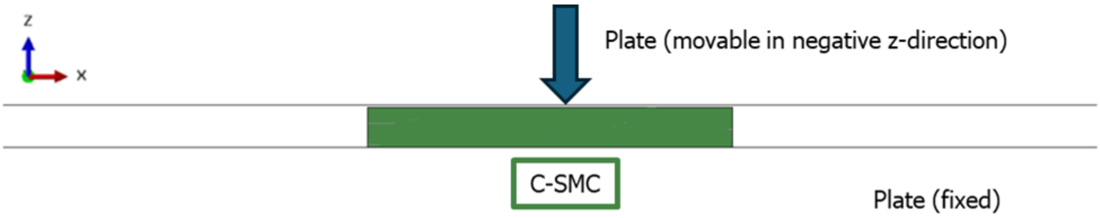

Figure 2: Assembly of the model: top plate movable along z-axis, bottom plate fixed with the initial fibre-matrix stack.

A fibre volume content of approximately 15% is used to examine the flow behaviour. To investigate size effects, the dimensions of the tool, the carbon-fibre bundles and the SMC stack are varied in relation to each other. The aim is to compare the flow behaviour of carbon-fibre bundles for the different DBS approaches, i.e. the new sub-bundle approach and the previous single-bundle approach. The analysis is performed for varying stack height, viscosity, and shear rate. The findings will be used to better understand the mesoscopic flow dynamics and the convergence behaviour of the DBS model and based on this, to model more complex C-SMC parts.

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