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Editorial

Each volume gathers contributions on specific topics:

Vol 1. Industrial applications
Vol 2. Material science
Vol 3. Material and Structural Behavior – Simulation & Testing
Vol 4. Experimental techniques
Vol 5. Manufacturing
Vol 6. Multifunctional and smart composites
Vol 7. Life cycle performance
Vol 8. Special Sessions

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This collection contains the proceedings of the 21st European Conference on Composite Materials (ECCM21), held in Nantes, France, July 2-5, 2024. ECCM21 is the 21st in a series of conferences organized every two years by the members of the European Society of Composite Materials (ESCM). As some of the papers in this collection show, this conference reaches far beyond the borders of Europe.

The ECCM21 conference was organized by the Nantes Université and the Ecole Centrale de Nantes, with the support of the Research Institute in Civil and Mechanical Engineering (GeM).

Nantes, the birthplace of the novelist Jules Verne, is at the heart of this edition, as are the imagination and vision that accompany the development of composite materials. They are embodied in the work of numerous participants from the academic world, but also of the many industrialists who are making a major contribution to the development of composite materials. Industry is well represented, reflecting the strong presence of composites in many application areas.

With a total of 1,064 oral and poster presentations and over 1,300 participants, the 4-day event enabled fruitful exchanges on all aspects of composites. The topics that traditionally attracted the most contributions were fracture and damage, multiscale modeling, durability, aging, process modeling and simulation and additive manufacturing.

However, the issues of energy and environmental transition, and more generally the sustainability of composite solutions, logically appear in this issue as important contextual elements guiding the work being carried out. This includes bio-sourced composites, material recycling and reuse of parts, the environmental impact of solutions, etc.

We appreciated the high level of research presented at the conference and the quality of the submissions, some of which are included in this collection. We hope that all those interested in the progress of European composites research in 2024 will find in this publication sources of inspiration and answers to their questions.

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EFFICIENT MICROMECHANICAL FE SIMULATION OF REAL COMPOSITE MICROSTRUCTURES UNDER LONGITUDINAL COMPRESSION

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Abstract
Microstructural imperfections, such as fibre waviness, voids, and notches, have been reported to impact greatly the performance of fibre-reinforced composites under longitudinal compression. To investigate the effect of real microstructural imperfections, micromechanical finite element models (μFEM) have been generated using data from micro-Computed Tomography (μCT) tests. Due to the increased computational cost, conventional μFEMs with continuum 3D elements fail to simulate large enough microstructures to be considered statistically representative. This study proposes an efficient μFEM using shell and beam elements to simulate the behaviour of the matrix and fibres respectively. The composite microstructure simulated with the Shell-Beam models uses 3D fibre paths from existing μCT experiments and represents a volume up to two orders of magnitude larger than existing μFEM in the literature. In this work, we present the methodology to construct Shell-Beam composite microstructures using fibre data from existing μCT tests and compare its results against conventional μFEMs found in the literature. The outcome showcases the benefit of using the Shell-Beam method to investigate the effect of real fibre imperfections on the behaviour of the composite under longitudinal compression.

1. Introduction

Micromechanical finite element modelling has been a well-established method to investigate the behaviour of fibre-reinforced polymer-matrix composites and the interaction of their constituents under external loading [1], [2], [3]. Under longitudinal compression, which exhibits a detrimental dependence on microstructural imperfections such fibre waviness and the presence of voids, there has been a considerable effort to simulate failure initiation and propagation, and to identify the key microstructural mechanisms leading to compressive failure.

While there is a vast literature on different types of micromechanical finite element models (μFEMs), e.g., single fibre, idealised multi-fibre, and "*realistic*" Representative Volume Elements (RVEs) based on micro-Computed Tomography (μCT) images, these models only contain up to a few tens of fibres and they are only a few hundred micrometers long [1], [2], [3]. The size of these virtual composite microstructures is limited by the computational cost of these models and, based on recent studies [4], is orders of magnitude below the critical size which can be considered statistically representative. This study proposes an efficient micromechanical finite element method, using shell and beam elements, to explicitly simulate the behaviour of the matrix and fibres respectively in a realistic composite microstructure under longitudinal compression.

2. Development of Shell-Beam micromechanical finite element model

2.1 Construction of Shell-Beam model and Boundary conditions

The improvement in computational efficiency is achieved by replacing the 3D continuum elements used in conventional μFEMs (in this study referred as Baseline models) with elements with reduced dimensionality, i.e., beams and shells. More specifically, to simulate the key mechanisms experienced under longitudinal compression, the constituents are modelled as:

- **Fibres:** Linear Timoshenko beam elements that can simulate the compressive, bending, and transverse shear deformation that occurs during fibre kinking. The cross-section is selected to be circular with homogeneous fibre diameter.
- **Matrix:** Quadrilateral four-noded shell elements with reduced integration and six degrees of freedom, which link neighbouring fibres and provide support through longitudinal shear.

To illustrate the development of these micromechanical models, a portion of a fibre database of a real composite microstructure from μCT images reported by Emerson *et al.* [5] is utilised as RVE. For a direct comparison of the proposed model to Baseline models, the RVE was relatively small, with a length of 350 μm and 47 fibres. An additional layer of 27 straight fibres was placed at the boundary of the RVE (to prevent spurious resin-rich regions and excessive twisting during longitudinal compression), and the Baseline model was embedded on a matrix cylinder with a radius of 46.5 μm.

To generate the Shell-Beam models, beam elements are created along the fibre paths obtained from μCT images, and Delaunay Triangulation networks (DTN) connecting the fibre centres are generated for each μCT section. The edges of consecutive triangulation networks are used to generate shell elements, representing the matrix region. This results in the development of Shell-Beam (SB) μFEM, featuring realistic wavy fibres and changes in neighbouring fibres. A characteristic example is shown in Figure 1, illustrating the fibre arrangement and the corresponding DTN for four μCT sections (as obtained from a portion of a composite microstructure from μCT presented by Emerson et al. [5]).

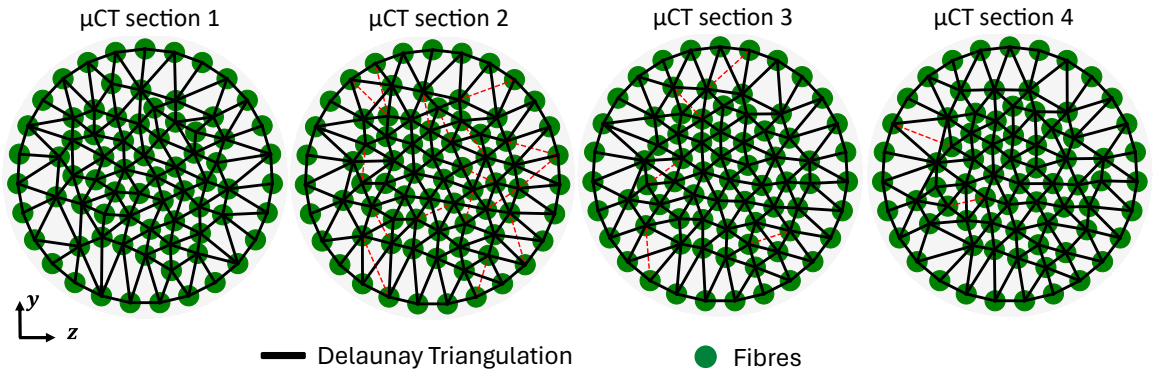

Figure 1. Four μCT sections of the used microstructure, distanced by 100 μm, showing fibres dispersed in a cylinder matrix, along with the corresponding DTN; a layer of boundary fibres has been added to the perimeter. The red edges show the orientation of the shell elements of previous μCT sections, revealing changes in fibre neighbourhood.

The SB-μFEM presented in this study are formulated in two variations: SB_s and SB_k. The SB_s variation places matrix elements linking inter-fibre centrelines directly, with beam and matrix elements sharing the same nodes. The SB_k variation places matrix elements in the inter-fibre spacing, and matrix elements do not share nodes with the fibre elements; this variation preserves the real matrix thickness in between neighbouring fibres and requires kinematic constraints to connect the fibre nodes and corresponding matrix nodes. The meshed geometries of all model variations, employing an element size of 5 μm along the fibre paths (x-direction), are shown in Figure 2, along with the boundary conditions used.

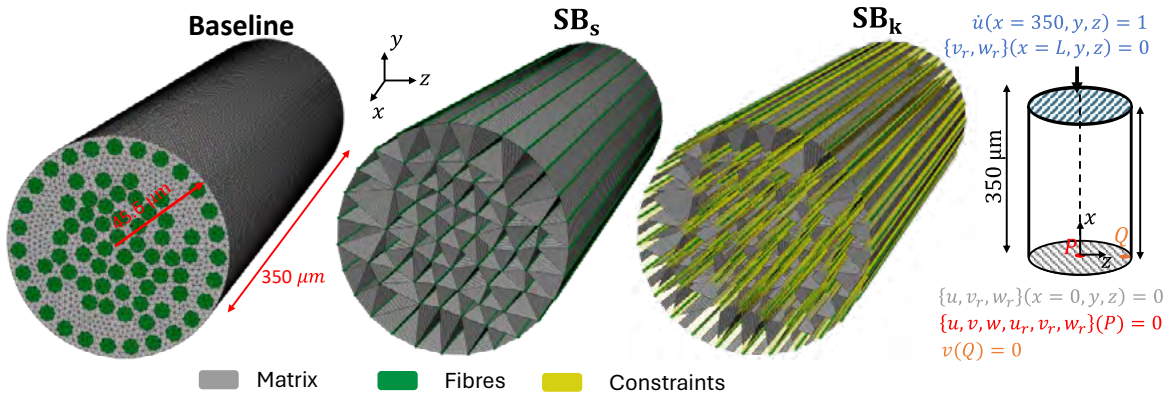

Figure 2. Meshed geometries with 75 fibres using the different model variations along with boundary conditions used. For the SB models the boundary conditions are applied to the fibre nodes. P is the fibre node close to the centre of the RVE, (x, y, z)=(0, 0, 0), and Q a fibre node close to the boundaries of the RVE, (x, y, z)=(0, 0, z_Q), with same y-coordinate as that of the Q.

2.2 Materials and calibration methodology

The constitutive model of the constituents used in this study were a transversely isotropic elastic law for the fibres (T300) and a non-linear elastic-plastic material (epoxy 682) for the matrix (with Von Mises criterion). The material properties of the carbon fibre and the ones of the resin were quoted from Csanádi *et al*. [6] and Sorini *et al.* [7] respectively, as summarised in Table 1.

Table 1. Input material properties for the T300 fibres [6] and the Epoxy 682 matrix [7].

Fibre	ϕ^f **[μm]**	E_1^f **[GPa]**	E_2^f **[GPa]**	ν_{12}^f	ν_{23}^f	G_{12}^f **[GPa]**	G_{23}^f **[GPa]**
T300	7	230	27.6	0.3	0.3	10.9	10.6
Matrix	E^m **[GPa]**	ν^m	$\sigma_{eq,yield}^m$ **[MPa]**	$\varepsilon_{eq,yield}^m$ **[%]**	$\sigma_{eq,max}^m$ **[MPa]**	$\varepsilon_{eq,max}^m$ **[%]**	
Epoxy 682	2.9	0.4	47.63	1.85	100.46	40.99	

To ensure the SB models accurately simulate the behaviour of the Baseline model, it is necessary to calibrate the constitutive law of the matrix. This calibration step is essential because the SB models represent the 3D volume of the matrix using discrete elements between the fibres, whereas the baseline models simulate the actual 3D volume. In addition, for the SB_s variation, the partial overlap of the matrix shell elements with the volume occupied by the fibres in the real composite changes the kinematic relationship between fibre rotations and matrix shearing, requiring further calibration.

The calibration of the matrix constitutive law requires running one Baseline μFEM of a hexagonal unit cell with sinusoidal misalignment under longitudinal compression and extracting the longitudinal shear stresses generated. For a detailed presentation of the calibration methodology and the steps required to compute the calibration constants, the reader is referred to authors' recent work [8].

3. Results

The homogenised longitudinal stress-strain response of the SB and Baseline μFEMs is presented in Figure 3. Comparing the stress-strain response of all models, the SB models predict the stiffness and strength relatively well, with maximum errors of less than 1 % and 7 % for the SB_k and SB_s models respectively. The shape of the snapback behaviour is also predicted relatively accurately, as shown by

the plots of Figure 3. The largest advantage of the SB models is demonstrated in terms of the simulation time, with an impressive improvement in computational efficiency of almost 99.8% and 99.9% observed for the SB_k and SB_s models respectively (when compared to time required for the Baseline to complete the simulation).

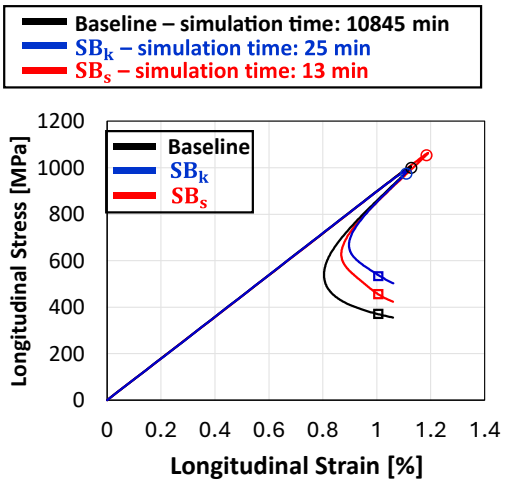

Figure 3. Homogenised longitudinal stress versus strain of the composite using the different model approaches: Baseline, SB_k, and SB_s. The increment corresponding to the maximum stress is shown by a circular marker "○"; the simulation time shown corresponds to the simulation up to the increment highlighted by a square marker "□".

The local longitudinal stresses of the fibres is depicted in Figure 4 (for the two increments highlighted in Figure 3, for all model variations). The results highlight the accuracy in predicting the local stress state of the fibres in terms of the location and absolute value of the maximum stresses throughout the kinking process. Based on Figure 4b, the fibres exceed their theoretical compressive strength in the location where kinking is observed, which is consistent for all model variations.

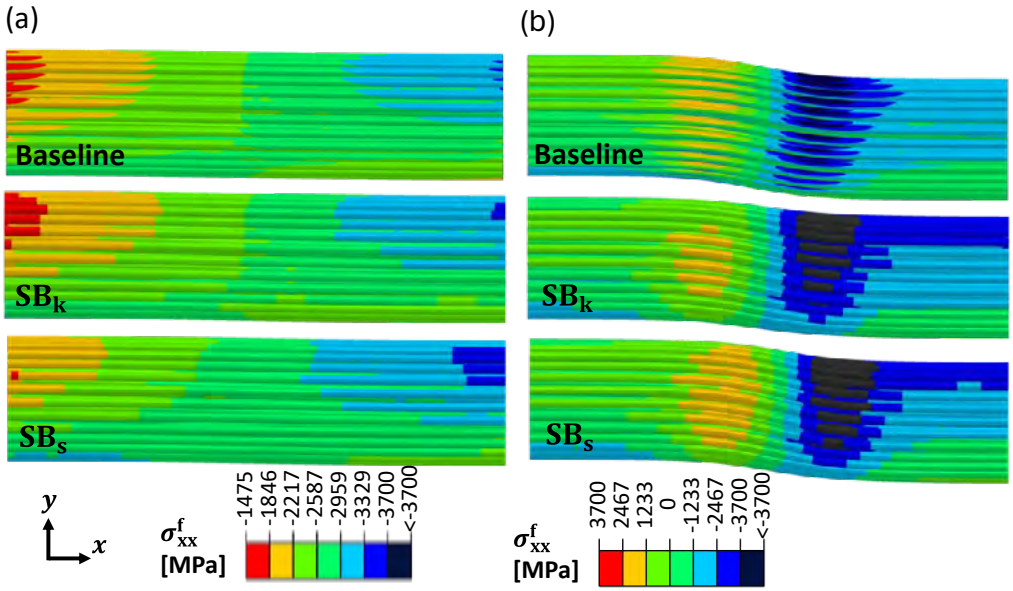

Figure 4. Longitudinal stresses of the fibres employing the different µFEM approaches corresponding to the increments highlighted in Figure 3 (Image (a): peak stress and Image (b): 1% global strain).

Similar accuracy results are reported for the local plastic equivalent strain fields among the different model variations, as shown in Figure 5. The strain fields of the SB models reveal that the locations where

maximum plastic equivalent strains occur are similar to those shown by the Baseline model. Additionally, comparing the strain fields between the two increments highlighted in Figure 3, the plastic equivalent strains evolve in a similar manner for all model variations.

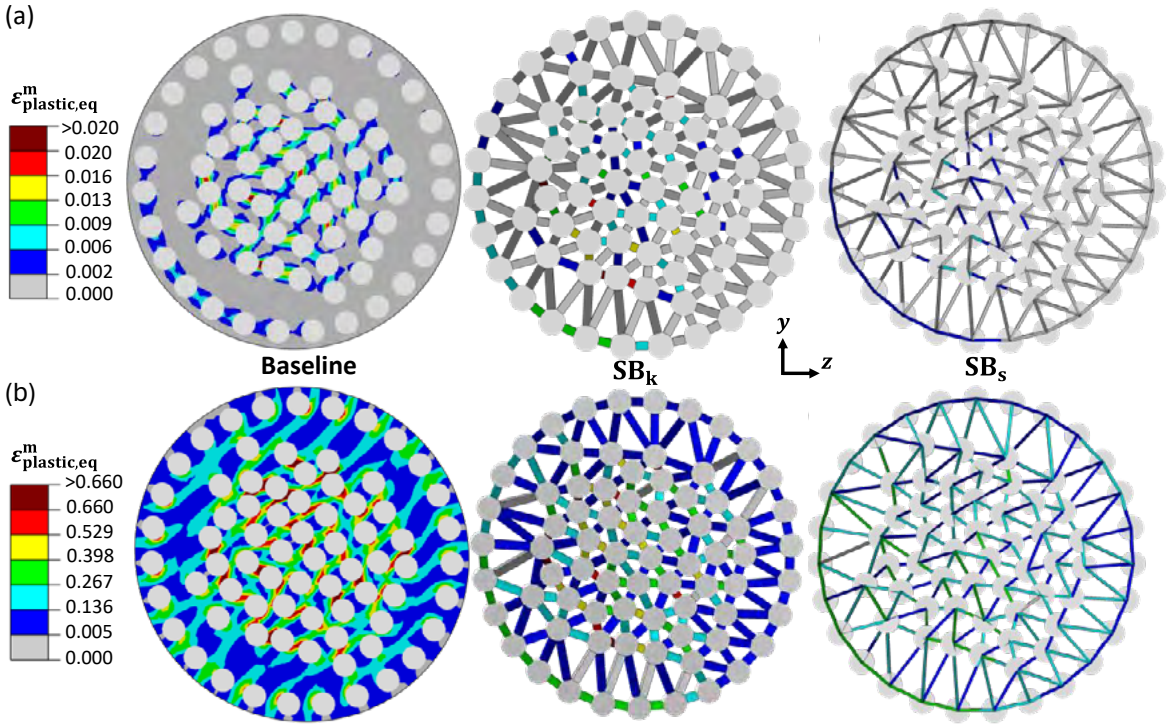

Figure 5. Plastic equivalent strains, $\varepsilon^{m}_{plastic,eq}$, of the matrix in the middle section of the RVE ($x = L/2$) for the different FE-model approaches corresponding to the global strain increments of Figure 3 (Image (a): peak stress and Image (b): 1% global strain). In all cases, the *SB* models are visualised accounting for the shell thickness (not in scale, scaled by a factor of "0.4") while the radius of the fibre is visualized in full scale.

4. Conclusions

An efficient micromechanical finite element method using Shell and Beam elements is proposed in this work to simulate real composite microstructures as obtained by μCT images. The proposed method is validated against conventional micromechanical models and showcases an impressive improvement, up to 99.9%, in computational efficiency. The use of the SB models can be a valuable computational tool to advance the knowledge around the effects of real composite imperfections on the compressive performance of the composite.

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