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MICROMECHANICAL MODELS FOR FABRICS AND COMPOSITES MADE OF HYBRID YARNS FROM RECYCLED CARBON FIBERS

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ABSTRACT

Although the great potential of carbon fibers for use in lightweight applications has been demonstrated in the past, their cost and environmental impact remain a barrier to their widespread use [1]. Recycling of carbon fibers from end-of-life components and combining them with thermoplastic fibers to form hybrid yarns addresses both issues. Due to the stochastic nature of hybrid yarns in terms of recycled carbon fiber (rCF) length and orientation [2], their influence on drapability and performance of rCF composites needs to be investigated. In this paper, a micromechanical model for analysing the dry and composite properties of yarns made from rCF is presented. By using a self-developed framework for generating representative volume elements (RVE) based on parameters such as fiber length, orientation, waviness, and fiber volume content, a variety of idealised random yarn geometries is created. A subsequent simulation step of the compaction of the RVE assures a more realistic RVE geometry. The models are validated by carrying out virtual tests and comparing the results with real tensile tests. The modelling approach can be used for further analyses.

KEYWORDS

Finite element method; hybrid yarns; micromechanical model; recycling carbon fibers.

INTRODUCTION

Due to their superiority over conventional material in terms of lightweight construction, carbon fiber reinforced plastics (CFRP) are applied in a wide range of industries, such as automotive, energy, and aerospace. Increasing demand is accompanied by an increase in carbon fiber waste, which negatively affects carbon fiber as a viable alternative, both economically and ecologically. Therefore, there is an urgent need for reliable recycling methods of carbon fibers.

The current industrially established processes use carbon fibers in randomly oriented nonwovens and injection moulded parts, which are only used in non-structural applications due to their limited mechanical properties [1]. Therefore, new processing strategies for recycled carbon fibers (rCF) that assure CFRP with high fiber orientation need to be explored. One of the most promising approaches uses the process chain of conventional spinning, which consists of carding, drawing and roving, and combines the rCF with thermoplastic fibers to spin hybrid yarns [3]. One of the main issues in this approach is the handling of CF during the processing. Due to the sensitivity of CF to transverse loads, partial damage is likely to occur during the processing steps. Therefore, the resulting fiber lengths in CFRP occur in form of a distribution [4], which both affects the drapability of textiles and the composite properties.

The evolution of CFRP has been accompanied by research into methods for predicting drapability and composite properties. The most advanced approaches describe composites at the micro-scale by modelling each fiber or a representative number of fibers. These approaches are used for continuous fibers [5,6] or short fiber composites [7,8]**.** A promising approach to model yarns made of long fibers with a low numerical effort is the Digital Element Approach (DEA), where a chain of beam elements approximates each fiber [9]**.** This approach has proven its capabilities in multiple cases [10,11]. There is a need to describe the mechanical behaviour of composite and textiles made of hybrid yarns based on flyer and DREF friction spun technology, taking into account the geometric properties of the elements. In the following work, an approach to model the idealised geometry of two types of hybrid yarns is presented. By modelling geometry at the fiber level, conclusions are drawn from micro geometry to the textile and composite behaviour. The results are compared to various tests to validate the model.

MATERIALS AND METHODS

In order to represent the yarn geometry in a representative volume element (RVE), a framework is developed to describe each fiber path. Each RVE is generated by giving information on their dimensions and shape. Components are added with information on their volume fraction as well as fiber length, orientation, path, and cross-sectional parameters. Similarly to the random adsorption algorithm [12], a nearest neighbour search algorithm assures no overlap between the fibers in the model. Fibers crossing the boundaries of the RVE are split at the boundary and moved to the opposite side of the boundary, ensuring periodicity of the unit cell. The algorithm can be run sequentially so that multiple types of RVE with different fiber geometries can be combined, enabling the generation of hybrid yarns. The feasibility of the described approach is exemplified for the geometries of flyer spun and friction spun yarns (Figure 1).

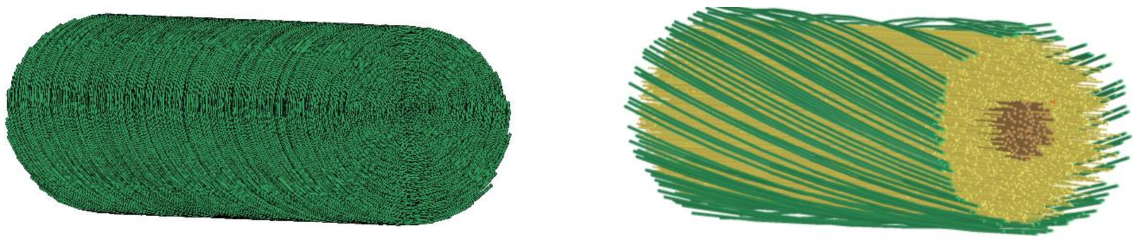

Figure 1. Examples of generated ring spun yarn (left) and DREF friction spun yarn (right).

For the ring spun yarn geometry, the composite properties were investigated. To limit the numerical effort, only one hybrid yarn is studied instead of modeling the entire composite of multiple yarns. A helix function [13] provides the idealized filament trajectory. An RVE length of 100 mm is chosen to assure that the full trajectory of each fiber is included. The diameter of the yarn model is chosen accordingly to measurements from real yarns.

The fibrogram method is used to obtain the fiber length distribution [4]. In order to obtain a more realistic geometry, further steps are carried out. To reproduce the yarn geometry in the composite, a compaction simulation is carried out using the explicit solver LS-DYNA. The final composite is then generated by coupling the compacted yarn in a solid matrix mesh with kinematic constraints [14] and applying periodic boundary conditions to nodes at the RVEs boundary. Finally, virtual tensile tests are carried out by applying a displacement on the model boundaries in the yarn axis direction, while constraining the remaining boundaries. The stresses and strains are homogenized and compared to real tensile tests. With the validated model, different parameter studies investigating the influence of fiber length and yarn twist are carried out.

For the friction spun yarn geometry, the influence of different processing parameters on the yarn deformation is investigated. The friction spun yarn is made of three different main components: an oriented core containing continuous thermoplastic filaments, a second core with staple carbon fibers, and a sheath structure made of thermoplastic fibers. The described geometry is modelled with an idealized unit cell geometry based on micrographs. The sheath structure is approximated by a helix structure. Its pitch taken from measurements of the mean fiber orientation based on images of the yarn. The initially generated uncompressed geometry is compacted by applying a fictitious thermal load to the sheath geometry, causing is to shrink and compact the yarn. An instantaneous tensile test ensures that the frictional contacts, which are important for the behaviour of the yarns, can take place correctly.

RESULTS AND DISCUSSION

Figure 2 displays the model processing steps and an exemplary real yarn. When excluding peaks at the model boundaries, the maximum filament stresses occur near the fiber ends. Because the composite failure is dominated by failure of the fibers, the overall failure also occurs at the same location. In Figure 3, a comparison between experimental and simulation data is shown. Compared to the experimental data, the simulation results agree well at low twists. At higher twist levels, the difference in tensile modulus increases, indicating a limitation of the idealized approach of the fiber geometry.

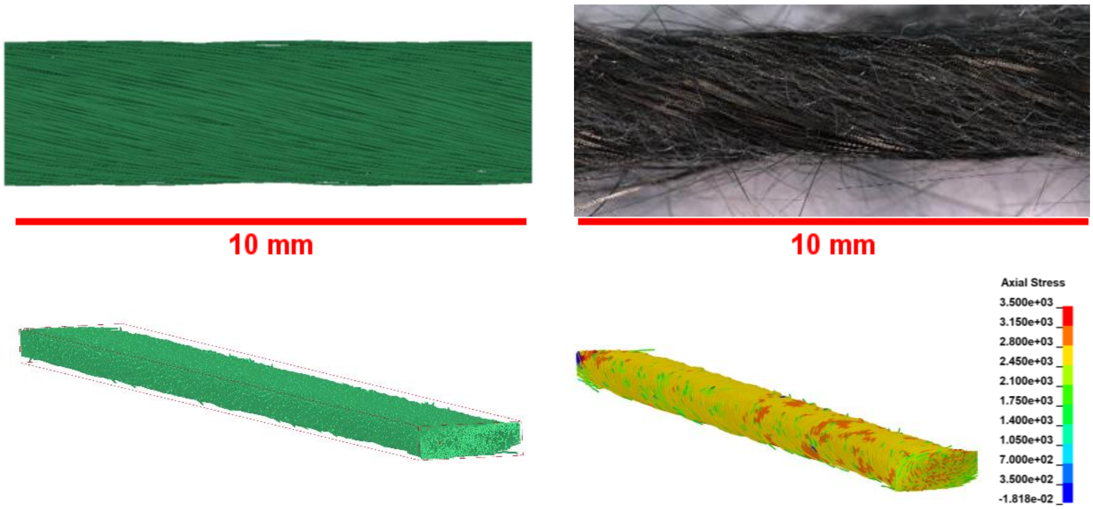

Figure 2. Modeling of the ring spun yarn geometry (Top: comparison of model with microscopic images, bottom left: composite model, bottom right: Axial stresses in each filament of spun yarn at the last time step before composite failure).

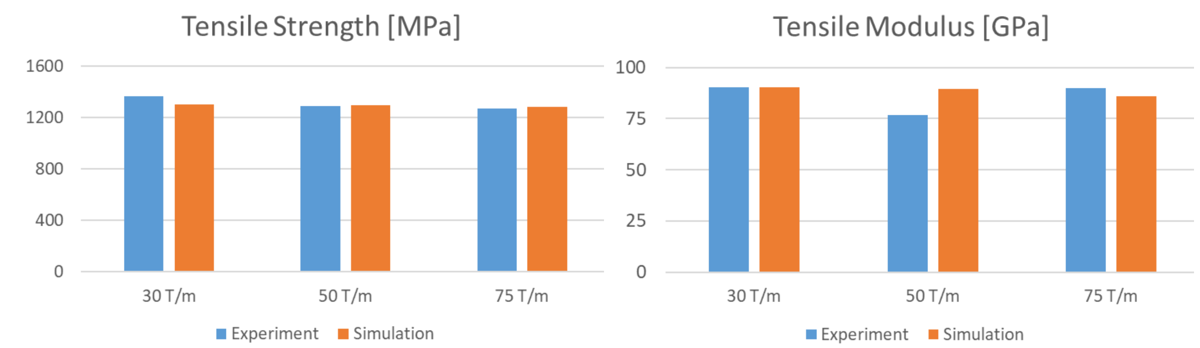

Figure 3. Comparison of virtual tensile tests and experimental data (left: strength, right: tensile modulus).

For the friction spun yarn geometry, the RVE geometry is reproduced by applying the thermal strain, resulting in a morphology closer to reality (Figure 4). Because of the idealized modelling of the sheath fibers, a more realistic RVE could not be achieved. Nevertheless the used approach is assumed to be sufficient to model the yarn deformation, which is dominated by the carbon fiber contact geometry.

In the next step, the influence of fiber contact geometry on its tensile properties is investigated.

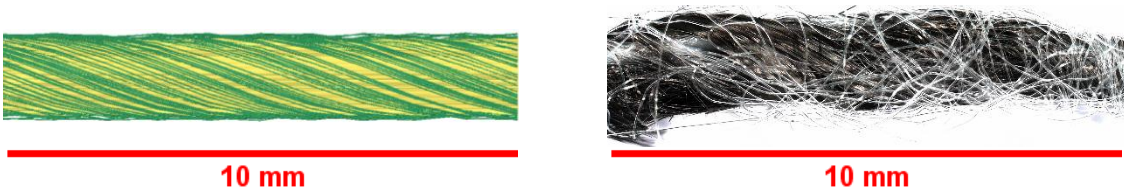

Figure 4. Comparison of friction spun yarn model results with microscopic images (left: model with scale in mm; right: real yarn)

CONCLUSION

In conclusion, the capability of micromechanical models to describe the geometry and mechanical behaviour of hybrid yarns and composites made of rCF is shown. The developed framework enables the creation of random RVEs made of fibers with a fiber length distribution based on process parameters, reducing the need of extensive tests. Mechanical properties of composites based on these thermoplastic hybrid yarns can be calculated with the developed framework. Results provide good correlation to experimental test, thus, enabling the models to be used for further analyses.

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