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Review

# Numerical forming of continuous fibre reinforced composite material: A review

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ABSTRACT

This article presents a survey of the literature about the numerical forming of continuous fibre reinforced composite material. This review shows that in spite of some models are defined with data from the meso-scale, all the numerical models of the forming process are computed at the macro-scale. This work highlights the numerical model versus the type of the model – continuous, discrete and semi-discrete approaches – as well as the understanding of the material behaviour – considered phenomena – and the forming process – draping, forming of prepreg and hot-forming.

## 1. Introduction

Continuous fibre reinforced composite materials are widely used in the space and aeronautical industries due to their high specific stiffness and low weight. The introduction into automotive industry is limited because of the high cost of fabrication and the low-volume manufacturing process. The thermoforming of continuous fibre reinforced composite panels is a low-cycle time, high-volume manufacturing process – taking typically less than two minutes to produce the final structure. This process is applied to composites with thermo-plastic resin which behaves visco-elastic at the ambient temperature and visco-plastic at higher temperature. Generally, the thermoforming process is applied to multilayer consolidated thermo-plastic composites. The composite sheet is heated to allow forming above the melting temperature of the resin. Secondly, the heated sheet is transferred to the forming tools. Then, the composite sheet is hot formed (stamped). The force applied to the composite stays constant during the cooling period. Finally, the formed structure is removed from the tool. A good understanding of each step is key to control the properties of the produced material. A review of the state of the art of the thermoplastic composite materials from the production of the material to the recent developments and products via the forming and the joining processes have been presented by Vaidya and Chawla [1]. An overview of the process and some benchmark and analytical methods have been presented by Sherwood et al. [2]. In addition, the thermoplastic matrix composites play upon these mechanical properties to take advantage on the point of view of the recyclability.

A predictive numerical model is useful to reduce the trial and error strategy during the definition of the forming process. The numerical model can be chosen into a wide range, from mapping model to multi-scale model chained with a consolidation model or a model of sheet production. A review of the numerical methods used to model the composite sheet forming process has been done by Lim and Ramakrishna [3]. According to the authors, these methods can be divided in two parts: the mapping approaches and the mechanical ones. The mapping model also called kinematic, fish-net or pin-jointed net methods is able to compute an approximation of the fibre orientation after forming process [4,5]. However, due to the mechanical behaviour it is not considered into the mapping model, the main defects as well as the wrinkling, cannot be predicted. This present work focusses on the models using the finite element method to solve the mechanical equations during the forming process. Due to the multi-scale nature of the composite material (see Fig. 1), numerical models have to be considered at different scales: at the macro-scale (the scale of the woven unit cell – mm), the meso-scale (the scale of the yarn – $10^{-1}$ mm) and the micro-scale (the scale of the fibres – μm). Mainly, multi-scale strategies can be split into two kinds: sequential and integrated computation strategies. With the sequential approach, first, the smaller-scale model is computed and then the results are used to solve the larger-scale problem. Before the computation of the numerical model, the material law is updated thanks to numerical results of the smaller scale. The main advantage of this approach is that the identified material law can be reused for several computations. On the other hand, the drawback is that the constitutive law has to be chosen a priori. Then the domain validity of the model is limited. With this approach, the smaller-scale model is only used to calibrate the behaviour of the main model. The

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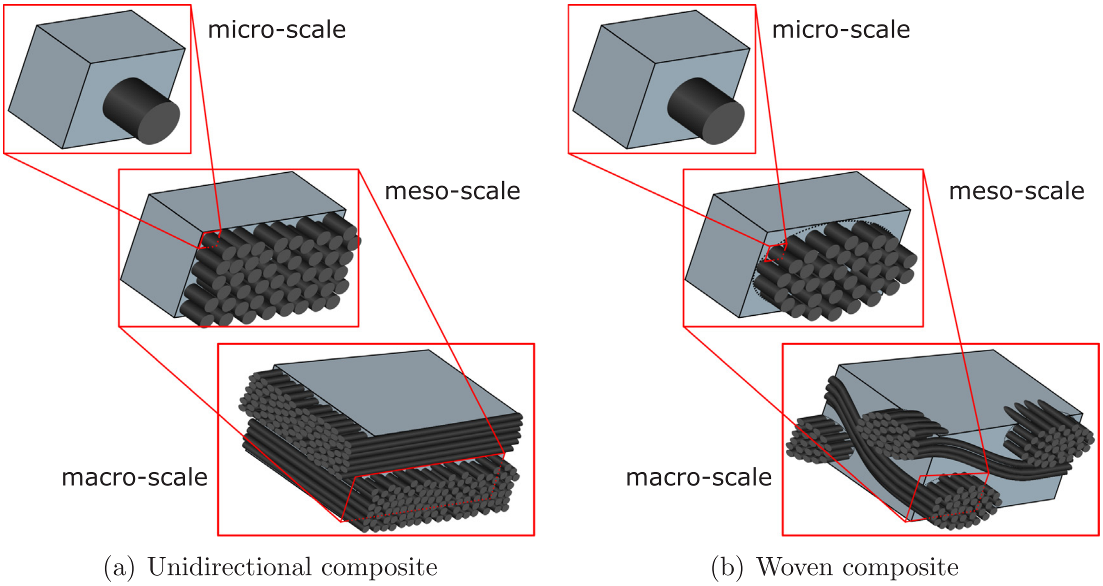

(a) Unidirectional composite (b) Woven composite

**Fig. 1.** Scheme of the multi-scale nature of the composite material – the scale of the fibres, few µm, between 5 and 10 µm for carbon fibre – the scale of the yarn or ply, between 0.03 mm and few mm and the scale of the woven or multi-ply, few mm. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

integrated strategy solves all scales simultaneously. The advantage of this approach comes from the constitutive law is free of any assumption. The main drawback is that the numerical cost is very high. The more popular multi-scale strategy is the finite element square ($FE^2$). With this numerical scheme, a smaller-scale problem is solved at each time steps, for each quadrature points of the problem. This smaller-scale problem is limited to an appropriate representative volume element (RVE). In other words, the quality of the computed results depends on the comprehensiveness of the model – the kind of phenomenon taken into consideration by the model. The choice of the model is a balance between the expected results and the allowed numerical cost.

In the optimisation of the numerical model only some phenomena or defects could be considered because of the numerical cost. The most critical types of defects that may appear during forming depend on the material as well as the parameters of the process. Nevertheless, the main defect occurring during the forming continuous fibre reinforced composite is the wrinkling. An important part of the studies has focused on only the prediction of the wrinkling. For example, the role of the three main rigidities (tensile, in-plane shear and bending) in wrinkling simulations has been analysed by Boisse et al. [6] and by Wang et al. [7]. However, different kinds of defects have been considered in the literature. The studies of Boisse et al. [8] and of Boisse et al. [9] have discussed about the onset of three types of defects (e.g. the wrinkling, the slippage between warp and weft yarns – the lack of fibres – and the transition zones which are directly related to the bending of the fibres). Each kind of defect has been studied with a different numerical model. Hallander et al. [10] have studied experimentally the influence of compression on the development of out-of-plane wrinkles. A double curved forming process with multilayer unidirectional prepreg has been studied versus some parameters – lay-up sequence, prepreg ply thickness, inter-ply friction and prepreg ply impregnation. The authors conclude that the lay-up sequence has a dominant effect on the wrinkling development due to the local fibre compression. Lightfoot et al. [11] also have studied experimentally the onset of wrinkling. The authors have proposed a new mechanism of wrinkle formation in layups of unidirectional plies. This mechanism has been supported through examination of high-resolution micrographs and subsequent classification of defects observed. Furthermore, the variability of voidage, resin content and surface roughness of uncured prepreg tapes has been experimentally studied by Lukaszewicz and Potter [12]. The aim of this study is to control the defects and produce material with low property variability. The relationship between void characteristics and material properties has been studied by Huang and Talreja [13]. The effective elastic constants have been computed over a volume cell with void modelling the observed void microstructure. On the other hand, the phenomena that happen during forming are still not well-known especially regarding the numerical simulations. The absence of the generally accepted model to simulate the forming process can be explained by the multi-scale nature and anisotropy of the material as well as the complexities of the coupling between the phenomena. A review of the numerical models of dry fibrous material at various scales versus the mathematical formulation has been presented by Syerko et al. [14] considering bending and tension and by Syerko et al. [15] regarding the shear behaviour. This makes the optimisation of the forming process, as well as the control of defects (e.g. wrinkling, lack of matrix, broken fibres, void), difficult. Consequently, in spite of the important number of scientific studies, further work is necessary to increase the reliability of the numerical models.

### 1.1. Objective

The objective of this review is to highlight the numerical model of the forming process of continuous fibre reinforced composite material to guide the choice of the more relevant versus the desired aim. The numerical models are classified regarding the type of model as well as the understanding of the phenomena and the forming process modelled. At the same time, the advantages and disadvantages of each kind of model are discussed to bring the future challenges and developments.

### 1.2. Outline

The main part of this review focused on the numerical forming process at the macro-scale level. At the current knowledge of the authors, no simultaneous multi-scale model has been developed to simulate the forming process. The models are classified into three categories. First, a review of the numerical models using the continuous approach is presented Section 2.1. Then, the numerical models with a discrete approach are reviewed Section 2.2. Finally, a review of the numerical models adopting a semi-discrete approach is exposed Section 2.3. Moreover, the methods used to calibrate these macro-scale models are