Multiscale finite element models for the analysis, design and optimisation of variable stiffness composites

Alberto Racionero Sánchez-Majano*

Mul^2 Lab
Department of Mechanical and Aerospace Engineering, Politecnico di Torino
Corso Duca degli Abruzzi 24, 10129 Torino, Italy

Abstract:

Different engineering fields have required the adoption of sophisticated and lightweight components in the last decades. Therefore, composite materials have shown an increased use not only in the aerospace industry but also in automotive and energy applications. Compared to metallic alloys, composites have a significant advantage due to their higher stiffness and strength-to-weight ratio. Related to aerospace engineering, in the first instances where composites were introduced, they were placed in secondary structures and manufactured by well-trained operators. In this regard, the very first components made of composites can be seen as craft pieces because of the low deposition rate.

The irruption of Automated Fibre Placement (AFP) and Automated Tape Laying (ATL) has increased the deposition rate and permitted the conceiving of new composite materials in which the fibres are no longer straight but can follow curvilinear paths. These are known as variable angle tow (VAT) or tow-steered composites. Although beneficial, this new class of composites leads to new modelling challenges. In this context, and due to these materials' hierarchical and multiscale behaviour, advanced numerical methods must be conceived to thoroughly analyse, design and optimise them.

Different modelling techniques are utilised accordingly because of the interaction between the scales in composites. For instance, at the component level, it is common to use classical lamination theories that predict the structure's global performance well. However, as soon as the engineer needs to investigate what is happening at the innermost scales, the fidelity of the analysis tools must be increased. At this stage, more computationally demanding models are required.

Due to the changes in the modelling strategies, new governing equations need to be generated for each scale. To avoid generating ad hoc equations for all the composite scales, one can employ the Carrera Unified Formulation (CUF). Based on CUF, this thesis derived numerical solutions based on the Finite Element Method (FEM) to investigate the component, layer and fibre scale of VAT composites. CUF permits deriving the governing equations for an arbitrary structural theory without making any a priori assumption. Because of this, the desired accuracy of the model can be defined as input of the analysis. With this procedure, the governing equations and the relative finite element arrays of one-dimensional (1D) and two-dimensional (2D) theories are formulated in terms of Fundamental Nuclei (FNs). The FNs are the building block of the proposed formulation. According to CUF, the three-dimensional (3D) field of displacements can be expressed as an arbitrary expansion of the generalised displacements. Various beam, plate and shell models can be implemented depending on the choice of the polynomials employed in the expansion. In this thesis, Taylor (TE), Lagrange (LE), and Hierarchical Legendre (HLE) polynomials have been considered for the kinematic models. Concerning the modelling, at the macroscale, of laminated structures, there exist two approaches: the Equivalent Single Layer (ESL) and Layer-Wise (LW) approach. This work has used TE to generate ESL models. In contrast, LE has been employed to generate LW models. Regarding meso

*PhD student. E-mail: alberto.racionero@polito.it

and microscale modelling, LE and HLE kinematics have been utilised to obtain embedded and classic Component-Wise (CW) models, respectively.

The first part of the thesis delves into the formulation of displacement-based high-order 1D and 2D theories for static analyses. In detail, the macro and mesoscale studies have focused on capturing accurately the stress state of VAT components. In contrast, the microscale models have investigated the retrieval of the homogenised effective properties of heterogeneous materials and the prediction of the stress state for the constituents of the composite material.

The second part is devoted to the fabrication process of tow-steered structures. In particular, the defects arising during the fabrication and their ultimate influence on the mechanical behaviour of the structure were investigated. Since these components are manufactured with hierarchical materials such as fibre-reinforced composites, defects can occur at different scales, i.e., fibre-matrix and layer levels. Furthermore, defects can be subdivided into uncertainty and deterministic flaws. Examples of the latter are the fibre volume fraction variability and misalignments. In contrast, gaps and overlaps are deterministic defects, as we can predict their position by simulating the AFP manufacturing process.

The last part of the thesis focuses on optimising the mechanical performance of VAT structures. Various features such as the fundamental frequency, buckling load, vertical deflection, strain concentration factor, and strength were optimised considering a defect-free condition. That is, uncertainty or deterministic defects were not considered in the optimisation. The latter were included subsequently to optimise the fundamental frequency to understand the difference between the various manufacturing conditions.

Keywords: Finite Element Method; Carrera Unified Formulation; Higher-order beam/plate/shell models; Composite materials; Variable stiffness composites; Multiscale; Embedded Finite Elements; Uncertainty quantification; Manufacturing defects; Optimisation.