Advanced multiscale models for the analysis of composite structures with applications to curing simulation and multiphysics

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Abstract:

Advanced composite materials play a fundamental role in aerospace design and represent the future of engineering applications thanks to their exceptional specific strength, stiffness, and tailorability, which ensure high and reliable performance under mechanical, thermal, electrical, and hygroscopic loads, making them suitable for smart structural concepts for future engineering applications. However, their successful use strictly depends on guaranteeing multiscale and multifield performance. Due to their intrinsic multiscale nature, a key challenge resides in linking microstructural mechanics to macroscopic response while accounting for coupled mechanical, thermal, moisture, and electrical effects. Modern components must, therefore, respond predictably to thermal gradients, moisture ingress, and smart-layer coupling, without incurring prohibitive analysis costs.

Multiscale tools often rely on computationally demanding analyses that limit their practical applicability. The need to develop a general, sustainable framework able to support future aerospace composites is the main driver of the present work. These tools must represent material anisotropy and lamination details, account for multiphysics sources, and transfer information across length scales without resorting to prohibitively expensive full three-dimensional (3D) resolutions.

The scope of the thesis is to build a horizontal knowledge across relevant scales and physics of the problem, enabling multiscale analysis as a true exchange of information between scales. To achieve this, analyses must be implementable and automatable, and unnecessary computational cost must be eliminated.

To this end, the work proposes a set of numerical tools developed from their formulations, through implementation and verification, offering a complete view of the workflow. Two complementary variational frameworks, the Principle of Virtual Displacements (PVD) and the Variational Asymptotic Method (VAM) via the Mechanics of Structure Genome (MSG), are adopted to build the governing equations, and the entire framework is integrated within the Carrera Unified Formulation (CUF).

The core of the work is CUF, adopted as a general generator of refined one- and two-dimensional models. Within CUF, the 3D displacement field is expanded through the thickness (for plates/shells) or over the cross-section (for beams) by means of Taylor (TE), Lagrange (LE) and Hierarchical Legendre (HLE) expansions. This yields families of Equivalent Single Layer (ESL), Layer-Wise (LW) and Component Wise (CW) theories obtained by increasing the expansion order only where the physics requires it. The approach retains the compactness of a single implementation by recasting the Finite Element (FE) matrices in terms of Fundamental Nuclei (FN), used as building blocks for any selected kinematics. Such flexibility proves decisive for laminates with strong through-thickness heterogeneity, variable angle tow (VAT) steering, free-edge effects, or local patches, where transverse stress recovery and interlaminar continuity demand high-order descriptions that classical low-order theories cannot reliably provide. CUF allows for a unique field adaptable and computationally tailorable procedure, making the instrument that allows us to achieve the scope of the work. Overall, the proposed CUF-PVD/VAM framework delivers a compact, scalable scheme that enables the computation of multifield effective properties and local fields at the microscale; prediction of thermal stresses and thermal buckling at the structural scale; and the estimation of process-induced distortions during manufacturing processes. By activating higher-order kinematics only where needed, the *method balances fidelity and computational cost and preserves a consistent variational basis across scales. The thesis is structured to progressively present the theoretical, numerical, and applicative framework developed throughout the research activity. Chapter 2 establishes the theoretical foundations for composite structural modelling, introducing the kinematics and constitutive relations for laminated and Variable Angle Tow (VAT) composites. Classical beam and plate theories are reviewed and extended into refined higher-order formulations through CUF. The chapter also presents the unified finite element implementation based on the concept of Fundamental Nuclei. Chapter 3 addresses the micromechanical scale by introducing VAM and MSG for multiscale and multifield analyses. It defines the Representative Unit Cell and associated boundary conditions, formulates variational problems for several coupled physical fields, and integrates CUF within MSG to enable the efficient transfer of effective properties and structural information. Chapter 4 focuses on the thermomechanical modelling within the PVD, presenting thermal stress, buckling, and curing-cycle simulations, and introducing micromechanical procedures for evaluating effective properties and defect sensitivity. Chapter 5 collects and discusses all the numerical results, encompassing CUF–MSG/VAM micromechanics, CUF–PVD applications, curing simulations, and preliminary analyses of a space antenna component. Finally, Chapter 6 summarizes the main findings, highlighting the original contributions and future research perspectives, while Appendix A lists the publications derived from the PhD work.*

Keywords: Multiscale simulations; Finite Element Method; Carrera Unified Formulation (CUF); Higher-order beam/plate models; Variable Angle Tow laminates; Multiphysics; Thermal buckling; Curing cycle simulation; Micromechanics with defects; Variational Asymptotic Method (VAM); Homogenization; 3D–2D dimensional reduction; Ultra-thin planar antennas.

Torino, 31/10/2025