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Virtual Manufacturing of Smart Composite Panels using CUF-Based Multi-Field Modeling

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Abstract. The manufacturing of composite structures is inherently complex due to the presence of coupled thermo-chemo-mechanical phenomena occurring during the curing process, which lead to residual stresses, distortions, and potential defects. These challenges become even more critical in smart composite panels with embedded sensors, where material heterogeneities and interfaces further increase stress concentrations and local effects. In this context, virtual manufacturing plays a key role, providing a powerful tool to explore innovative design solutions, optimize process parameters, and mitigate manufacturing-induced defects without relying exclusively on costly experimental campaigns. Traditional modelling approaches, such as Classical Lamination Theory or first-order shear deformation theories, are often inadequate to accurately capture through-the-thickness behaviours and localized phenomena induced by embedded devices. In particular, they fail to properly represent interlaminar stresses, material discontinuities, and the interaction between different physical fields, which are crucial for the reliable design of smart structures.

To overcome these limitations, the Carrera Unified Formulation (CUF) offers a unified and versatile framework for the development of refined structural models. By enabling layer-wise kinematic descriptions and hierarchical expansions, CUF allows accurate prediction of three-dimensional stress and displacement fields with reduced computational cost. Moreover, its capability to incorporate multi-field couplings makes it particularly suitable for the analysis of smart composite structures with embedded piezoelectric sensors, accounting for both mechanical and electro-mechanical interactions during the manufacturing process. The proposed approach is applied to the virtual manufacturing of composite panels with embedded sensors, where the curing process is simulated through advanced constitutive models. The results demonstrate the ability of the framework to predict residual stresses, process-induced deformations, and local effects at the sensor–matrix interface. Furthermore, the coupled electro-mechanical analysis enables the evaluation of capacitance variations, providing a basis for real-time monitoring of the curing process.