

Advanced Multi-Field Modeling for the Virtual Manufacturing of Layered Structures with Embedded Sensors

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Abstract. This study presents a multi-physics modeling framework based on the Carrera Unified Formulation (CUF) within a virtual manufacturing environment to analyze the effects of embedded sensors in composite structures. The proposed layer-wise approach enables high-fidelity representation of the sensor-structure interface, accurately predicting interlaminar stress distributions and residual deformations around the sensor. By incorporating a multi-field electromechanical description, the model enables real-time monitoring of the curing process by tracking capacitance variations, thus providing a direct evaluation of the degree of cure. Furthermore, the framework predicts the development of residual stress fields induced by sensor integration, offering critical insights into local stress concentrations that could affect structural performance. The results highlight the importance of advanced modeling techniques for minimizing stress accumulation and optimizing the integration of sensors. Finally, the study demonstrates how virtual manufacturing environments can improve sensor placement strategies, enhancing the overall reliability and longevity of smart composite structures.

Key words: Embedded Sensors, Structural Health Monitoring, Virtual Manufacturing, Carrera Unified Formulation, Multi-field Model

1 INTRODUCTION

The integration of embedded sensors into composite materials represents a significant advancement in the field of structural health monitoring (SHM), offering enhanced capabilities in damage detection, system diagnostics, and real-time monitoring [1, 2]. However, the inclusion of such sensors introduces challenges during manufacturing, particularly stress concentrations and residual deformations, which can compromise the mechanical integrity of the structures [3].

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Composite manufacturing processes involve complex thermal and chemical cycles that induce free strains due to thermal expansion and resin shrinkage. The mismatch of these free strains across material phases and interfaces leads to the development of residual stresses and deformations, particularly significant in curved geometries such as L-shaped laminates [4]. Process-induced deformations, such as spring-in and warpage, are closely linked to the evolution of material properties during cure and the tool-part interaction [5].

Traditional modeling approaches, such as Classical Lamination Theory (CLT) and First-order Shear Deformation Theory (FSDT), are often insufficient to capture through-the-thickness deformations and local effects induced by sensor embedding. To overcome these limitations, the Carrera Unified Formulation (CUF) provides a powerful and versatile modeling framework that allows for refined kinematic descriptions and multi-field coupling [6]. Layer-wise models developed within CUF enable detailed evaluation of interlaminar stresses and localized phenomena without the need for computationally expensive full 3D models [7, 8].

Recent studies have shown that the integration of embedded piezoelectric sensors not only affects the mechanical performance but also alters the electrical response of the structure, such as variations in capacitance [9]. The capacitance change, sensitive to local stress states, offers an additional non-invasive metric for monitoring the structural integrity during and after manufacturing. However, classical models fail to predict this behavior accurately, highlighting the necessity of refined electro-mechanical coupling models [10, 11].

To address these challenges, multi-physics virtual manufacturing frameworks have been proposed, combining thermo-mechanical and electro-mechanical analyses to simulate the manufacturing process of smart composite structures [12, 3]. These frameworks allow for the accurate prediction of residual stresses, spring-in deformations, and sensor performance, enabling optimized sensor placement and manufacturing strategies.

This study builds upon previous efforts and presents an integrated methodology for the virtual manufacturing of layered structures with embedded sensors. By exploiting the capabilities of CUF-based refined models, it aims to provide a high-fidelity prediction of process-induced phenomena, offering insights into the effects of embedded devices on the structural and functional performance of smart composites.

2 ADVANCED NUMERICAL MODEL

The numerical framework employed in this study is based on a refined one-dimensional model developed within the Carrera Unified Formulation (CUF). The approach enables the accurate description of through-the-thickness displacement and stress fields using a layer-wise (LW) expansion.

The three-dimensional displacement field $\mathbf{q} = [u_x, u_y, u_z](x, y, z)$ is approximated by a hierarchical expansion over the beam cross-section, leading to the one-dimensional form:

$$\mathbf{q}(x, y, z) = \mathbf{F}_\tau(x, z) \mathbf{q}_\tau(y), \quad (1)$$

where $\mathbf{F}_\tau(x, z)$ are the cross-sectional expansion functions, and $\mathbf{q}_\tau(y)$ are the generalized one-dimensional unknowns.

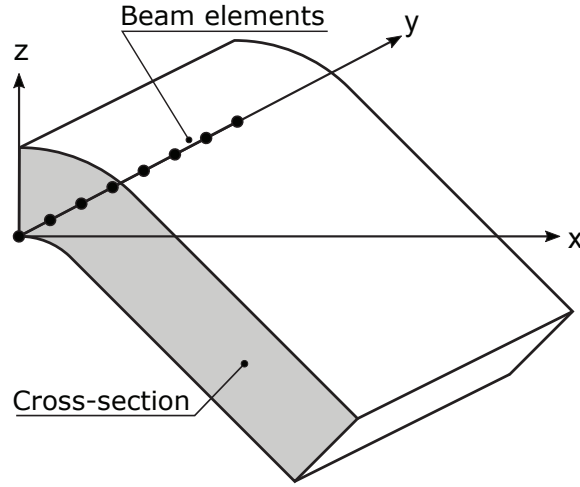


Figure 1: Reference system .

In this work, Lagrange polynomials were used as expansion functions $F_\tau(x, z)$ to achieve a layer-wise representation of the section.

The finite element discretization along the beam axis y was performed using standard shape functions $N_i(y)$, resulting in the following FEM approximation of the displacement field:

$$\mathbf{q}(x, y, z) = N_i(y) \mathbf{F}_\tau(x, z) \mathbf{q}_i\tau, \quad (2)$$

where $\mathbf{q}_\tau^i$ are the nodal unknowns associated with the generalized displacements.

The mechanical response of the composite panel during the curing process was modeled using a Cure Hardening Instantaneously Linear Elastic (CHILE) constitutive model, capturing the evolution of the material properties as a function of the degree of cure. The interaction between the composite part and the steel tool was modeled by introducing a shear layer, with a thickness equal to one-tenth of a ply thickness.

The resulting finite element problem was solved through an iterative procedure to account for the curing-dependent material behavior, as schematically illustrated in Figure 2. A fully coupled electro-mechanical model, see [9], has been used to predict the variation of the capacitance in the sensor.

3 NUMERICAL RESULTS

In this section, the main numerical results obtained from the virtual manufacturing simulations are presented. The effects of the embedded sensor on the mechanical response of the composite panel are first analyzed. Subsequently, the evolution of the electrical response during the curing process is investigated through capacitance monitoring. The results aim to validate the proposed modeling strategy and highlight the potential of the developed framework for real-time process tracking and structural performance assessment.

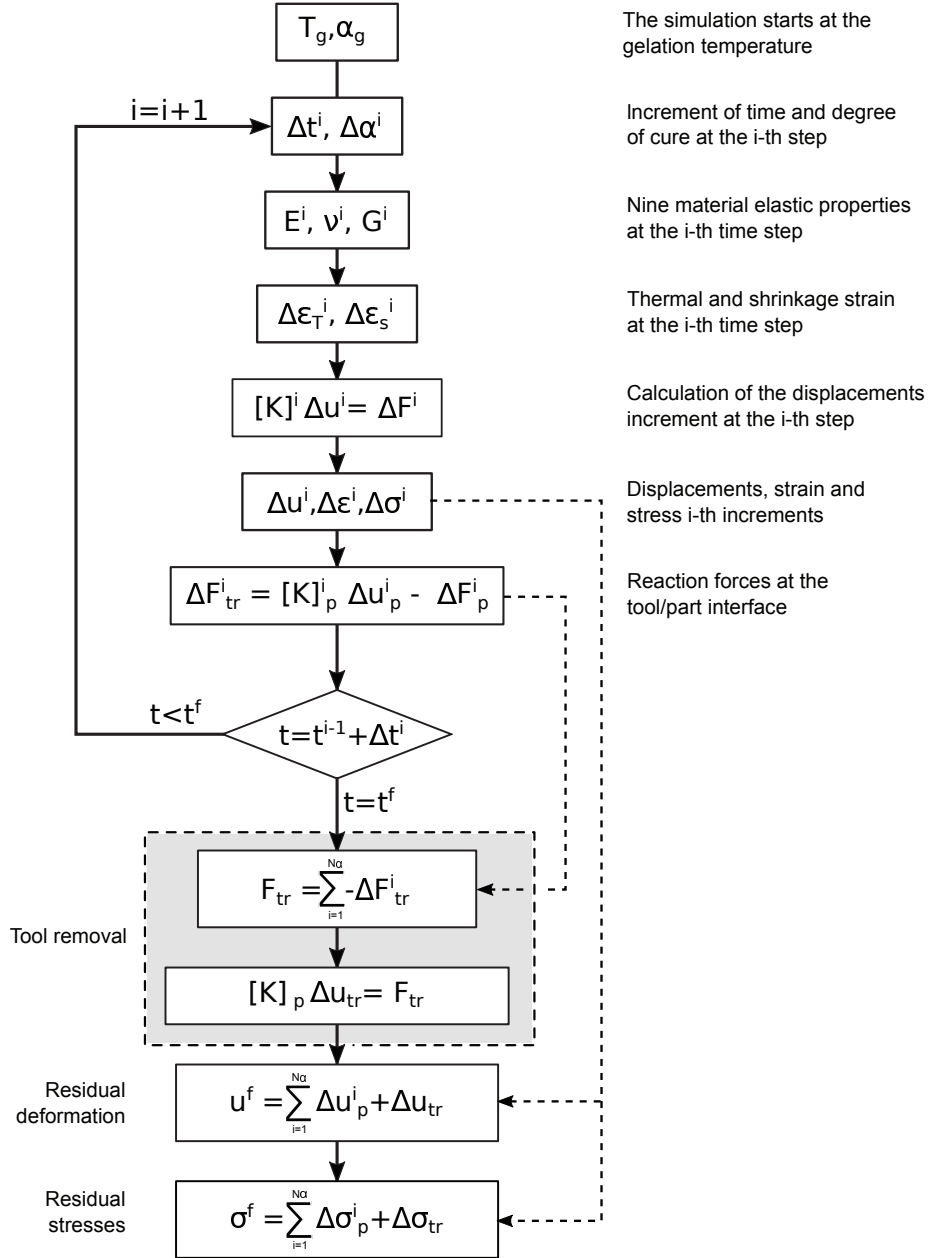


Figure 2: CHILE Numerical solution scheme [4].

Table 1: Mechanical and thermal properties of the steel tool and the ZPT-H5 sensor.

Property	Steel	ZPT-H5
Young's Modulus [GPa]	210	63
Poisson's Ratio [-]	0.30	0.31
Thermal Expansion Coefficient [$\mu\text{m}/\text{m}^\circ\text{C}$]	12	3.5
Density [kg/m^3]	7850	7700

3.1 Virtual manufacturing of a composite panel with an embedded sensor

The system under investigation consists of a composite panel made of eight plies of AS4/8552 material, laminated in a symmetric $[0/90/0/90]_s$ stacking sequence. The panel rests on a steel tool with a thickness of 0.01[m], and a shear layer is introduced at the tool-panel interface, with a thickness equal to one-tenth of that of a single composite ply. Two configurations were analyzed: in the first, the panel is free from inclusions; in the second, a ZPT-H5 piezoelectric sensor is embedded at the mid-plane of the laminate. The properties of the materials of the sensor and the tool are reported in Tab. 1 while the properties of the composite material can be found in [4].

The curing cycle considered consists of a single holding phase at 180°C . Detailed information about the curing parameters can be found in the literature [4]. The geometry of the embedded sensor is depicted in Figure 3.

A beam layer-wise model based on Lagrangian expansions was employed to accurately capture the multilayered behavior of the composite panel. Quadratic nine-node elements (Q9) were used to discretize the cross-section of the beam, allowing an accurate representation of the displacement and stress fields across each ply and the embedded sensor. Along the beam axis, a single three-node beam element (B3) was adopted, assuming that the variations along the longitudinal direction, y , can be considered negligible.

Symmetry boundary conditions were imposed at $x = 0$, and at $y = 0$ and $y = 1.667 \text{ mm}$ u_y have been set equal to zero. These constraints exploit the physical and geometrical symmetries of the problem, thus reducing the computational cost while maintaining the accuracy of the simulation.

To assess the impact of the embedded sensor, the displacement fields were evaluated. All results refer to the post-demolding condition. Figure 4 shows the vertical displacement field (u_z), highlighting how the presence of the sensor modifies the shrinkage behavior of the panel, as the piezoelectric material does not undergo significant curing shrinkage.

Figure 5 presents the in-plane displacement field (u_x), revealing that the embedding of the sensor also affects in-plane deformations, particularly at the interface between the composite and the piezoelectric material. A detailed profile of vertical displacements is provided in Figure 6. The value of the vertical displacement has been reported along the thickness of the panel. The negative value is due to the shrinkage of the material due to the curing process. The picture clearly shows that the sensor region does not experience vertical shrinkage.

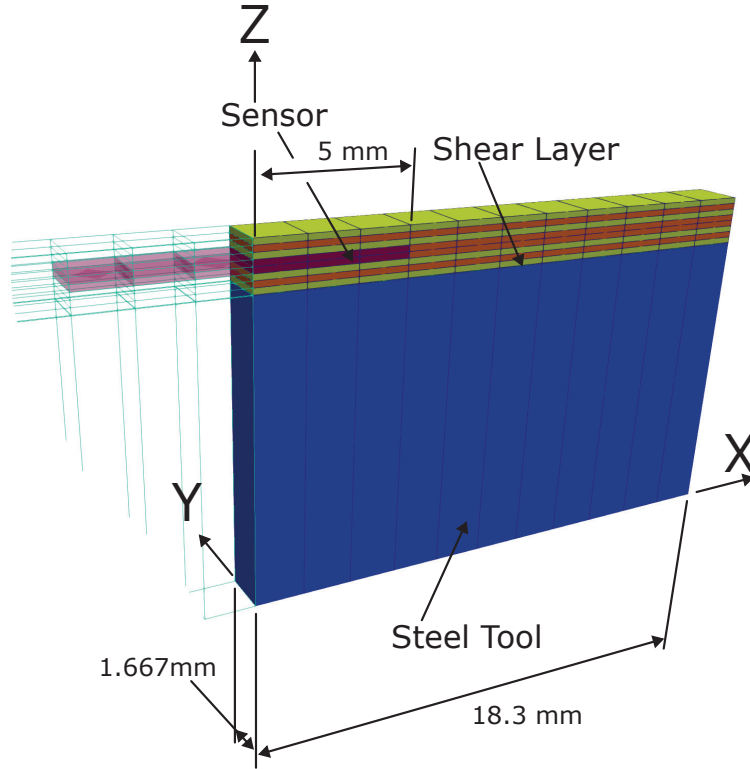


Figure 3: Geometry of the embedded ZPT-H5 sensor within the composite panel.

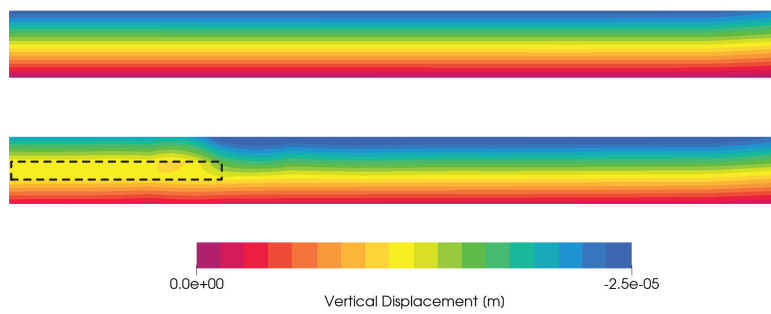


Figure 4: Vertical displacement field u_z : comparison between panel without (top) and with (bottom) embedded sensor.

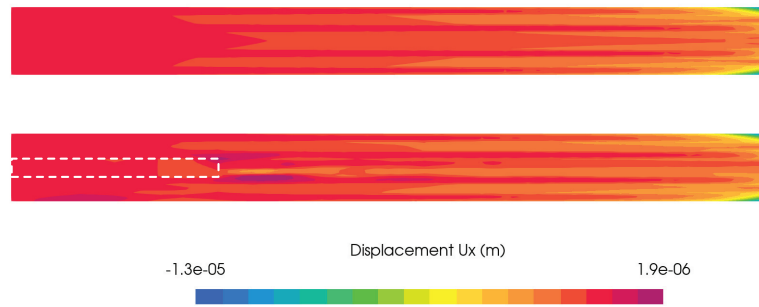


Figure 5: In-plane displacement field u_x : effect of the embedded sensor at the material interface.

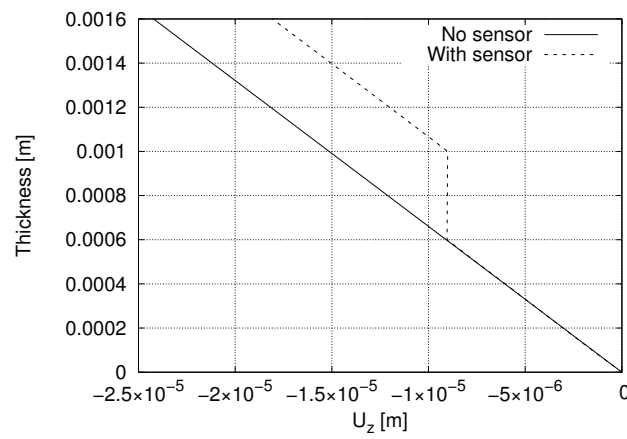


Figure 6: Vertical displacement profile u_z across the panel thickness. The region corresponding to the sensor shows no vertical displacement.

3.2 Real time estimation of the curing process via capacitance monitoring

Following the methodology presented in [9], for the configuration under investigation, the variation of the sensor capacitance was evaluated at each step of the curing process. A potential difference of 1 V was applied across the embedded piezoelectric transducer. In this case, the generated electric charge depends not only on the dielectric properties of the material but also on the mechanical stresses, as the piezoelectric material produces additional electric charges in response to the developing stress field. This surplus of electric charge results in a measurable variation of the sensor capacitance.

Figure 7 illustrates the temporal evolution of the degree of cure and of the transverse elastic modulus E_t . The modulus increases at first for the polymerization process and after $t = 200s$ a second variation of the modulus is due to the cool down phase. In Figure 8, the percentage variation of the capacitance value is reported as a function of the evolving transverse elastic modulus.

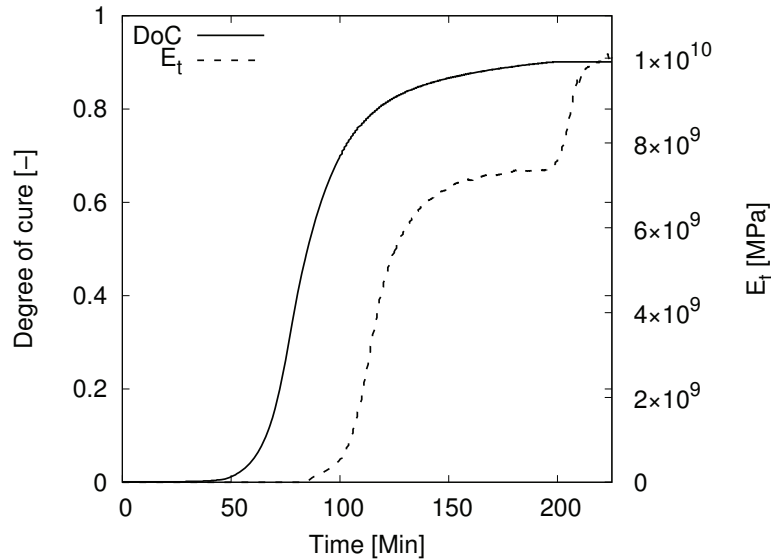


Figure 7: Temporal evolution of the degree of cure and the transverse elastic modulus E_t during the curing process.

The results show that the proposed approach allows an accurate tracking of the curing process. The numerical model adopted is the same described previously, based on a beam layer-wise approach with Lagrangian interpolation functions and quadratic elements for the cross-section discretization.

4 CONCLUSIONS

In this work, an advanced numerical framework based on a layer-wise model developed within the Carrera Unified Formulation (CUF) was employed to simulate the virtual manu-

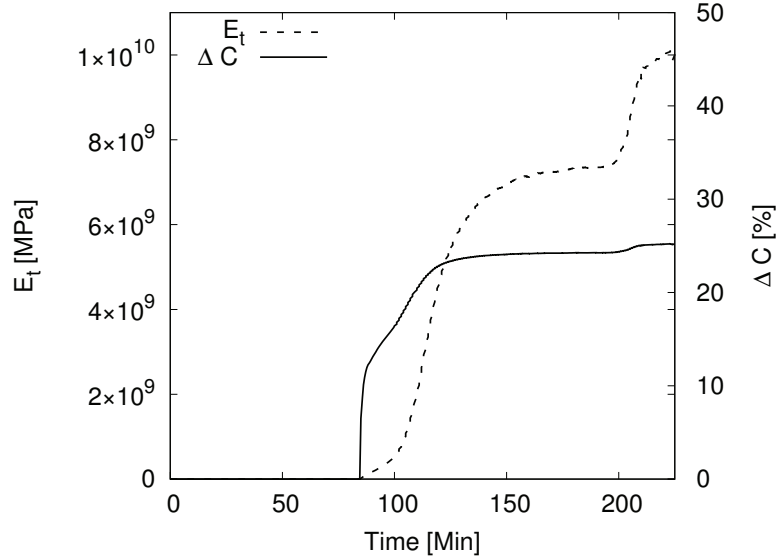


Figure 8: Percentage variation of the sensor capacitance as a function of the transverse elastic modulus E_t .

facturing of composite structures with embedded piezoelectric sensors. The methodology accurately captured the complex interactions between mechanical, thermal, and electrical fields during the curing process. The CHILE constitutive model was used to account for the evolving material properties, while the tool-part interaction was modeled through a dedicated shear layer. Furthermore, a fully coupled electro-mechanical analysis was performed to monitor the evolution of the sensor capacitance throughout the process.

The numerical results demonstrated the significant impact of the embedded sensor on both the mechanical and electrical responses of the structure. The presence of the sensor locally altered the shrinkage behavior, leading to variations in the displacement fields, especially around the sensor region. Moreover, the monitoring of capacitance variations proved to be an effective non-invasive technique to track the curing progression, with a clear correlation observed between the capacitance change and the evolution of the transverse elastic modulus.

Future developments will focus on extending the current framework to more complex geometries and multi-sensor configurations. In addition, the integration of damage initiation and propagation models within the virtual manufacturing environment will allow for a more comprehensive prediction of the long-term structural performance of smart composite structures.

Acknowledgements

This work was supported by the project “An AI-assisted virtual manufacturing approach to mitigate defects in advanced composites” funded by the Italian Minister of Foreign Affairs and INTERNATIONAL COOPERATION (MAECI) [grant number US23GR12].

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