

Efficient Surrogate Modelling of Fully Coupled Thermomechanical Behavior of Composite Materials

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Introduction

Thermoplastic composite materials exhibit highly dissipative behaviors such as plasticity, viscoelasticity, viscoplasticity, and damage, especially when subjected to complex conditions involving temperature, humidity, and loading [1]. These processes generate significant heat due to energy dissipation, which, in turn, influences the mechanical response of the composite. As a result, the interaction between thermal and mechanical fields becomes crucial, particularly under complex and cyclic loading conditions. This thermo-mechanical coupling is essential to consider, especially for composites with thermoplastic polymer matrices, to ensure accurate predictions of their behavior under real-world conditions.

While traditional multiscale frameworks, such as FE², effectively capture the coupled thermomechanical behaviors of composite materials [2, 3], their high computational cost remains a significant barrier for large-scale simulations. To overcome this challenge, an efficient surrogate model based on Artificial Neural Networks (ANN) can be developed to replace the costly FE computations at the microscopic scale. This approach aims to create a reduced-complexity multiscale modeling framework that combines FE and ANN techniques (Figure 1), enabling faster and more efficient simulations of composite structures. In this context, the Multiscale Thermodynamics Informed Neural Networks (MuTINN) framework emerges as a promising solution. Originally developed to model the elastoplastic behavior with damage in 2D woven composites, MuTINN leverages thermodynamic principles and ANNs to construct a macroscopic surrogate model for composite materials [4]. The framework integrates two neural networks: one to describe the evolution law and the other to capture the state law while introducing a penalty in the loss function to ensure the thermodynamic principles.

This work aims to extend the MuTINN framework to model the fully coupled nonlinear thermomechanical behavior of composite structures. Retaining its foundational approach of leveraging macroscopic quantities to represent the history-dependent behavior of composites, the enhanced model incorporates additional input parameters such as temperature, time, and entropy to account for viscoplastic effects. Validation of the enhanced model against mean-field Mori–Tanaka scheme combined with TFA theory [5] demonstrates its robustness and predictive accuracy across multiple material scales. For instance, simulations of a composite tube subjected to complex cyclic loading reveal a significant reduction in computational cost compared to traditional FE² methods, without compromising precision.

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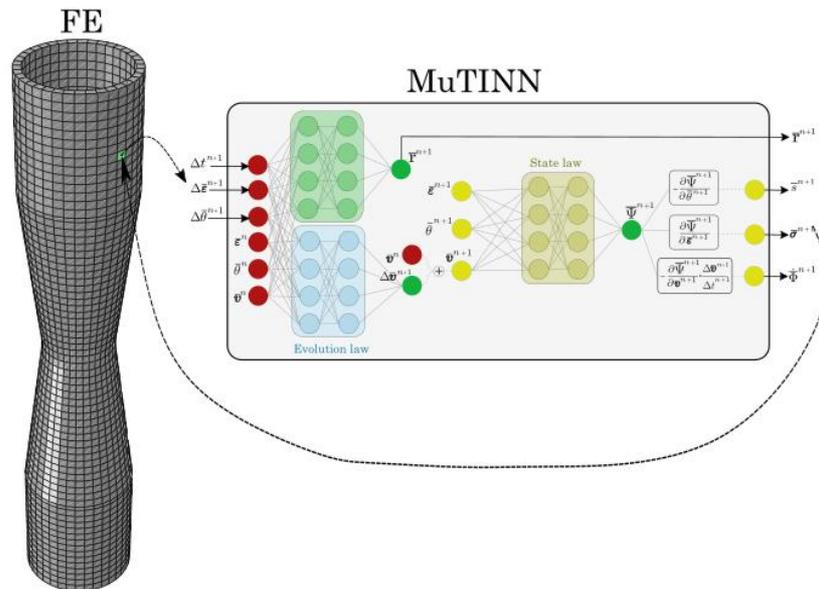


Figure 1: FE-MuTINN for simulating the fully coupled thermomechanical behavior of composite structures.

References

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