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Crain: A Physics-Informed Framework for Real-Time Multi-Scale Failure Prediction in Composite Materials Under Dynamic Loading

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Abstract

Accurately predicting multi-scale failure mechanisms in composite materials under dynamic loading remains a grand challenge due to the need to capture microscale damage mechanisms and macroscale structural responses, often with prohibitive computational cost. This paper introduces Crain, a novel hybrid framework combining physics-informed micro-damage modeling, reduced-order macroscale simulation, and experimental validation, enabling real-time predictions. Crain integrates microstructural damage evolution (fiber–matrix delamination, matrix cracking), dynamic simulator coupling, and validation loops, validated for crash-relevant aerospace and automotive composites. Results demonstrate high accuracy, efficiency, and applicability in engineering contexts, moving toward safer, lighter, and more resilient composite structures.

Keywords: *Composite materials, Multi-scale modeling, Failure prediction, Dynamic loading.*

1. Introduction

Composite materials, such as carbon fiber-reinforced polymers (CFRPs), are increasingly applied in aerospace, automotive, and defense industries due to their high specific strength and energy absorption capabilities. However, under dynamic loading conditions—such as impacts, shocks, or crash events—predicting when and how these materials fail remains an unresolved issue.

Traditional finite element models either oversimplify microscale interactions (e.g., fiber–matrix delamination) or demand prohibitive computational resources for real-time applications (Zhu et al., 2024). Multi-scale modeling methods, such as the Generalized Method of Cells (GMC), have shown promise in capturing microstructural responses embedded within macro-scale models (Li et al., 2024). Likewise, hybrid discrete–continuum approaches (Gupta et al., 2006) and multiscale recursive micromechanics frameworks (Pineda et al., 2022) have advanced progressive failure predictions. Yet, computational inefficiency and limited scalability persist.

This paper introduces Crain, an integrated computational framework designed to bridge this gap. By combining microstructural physics-informed modeling with reduced-order macroscale simulation, Crain enables real-time, validated predictions of failure in composite structures under dynamic loading.

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2. Research Objectives

The study is guided by five objectives:
1. Develop micro-scale models of fiber–matrix interactions and damage initiation.
2. Construct reduced-order macroscale models that dynamically update based on microstructural state.
3. Integrate micro- and macro-models into a unified real-time simulation framework (Crain).
4. Validate predictions against experimental data for composites under impact and dynamic loading.
5. Demonstrate applications in aerospace and automotive crash safety design.

3. Methodology

3.1 Micro-scale Modeling

Crain incorporates GMC-based modeling to capture local microstructural failure modes (Li et al., 2024). This includes fiber–matrix debonding, delamination, and microcrack initiation. Interface phase effects are modeled using cohesive elements and stress amplification methods (Wang et al., 2025).

3.2 Reduced-Order Macroscale Simulation

Macroscale structural response is predicted using reduced-order models inspired by multiscale recursive micromechanics (MsRM). This approach balances fidelity with computational efficiency, enabling real-time simulation (Pineda et al., 2022).

3.3 Simulator Framework

Crain employs a coupled loop in which micro-scale failure parameters update macroscale stiffness matrices dynamically. Adaptive time-stepping ensures stability and computational feasibility.

3.4 Experimental Validation

Validation is carried out through dynamic impact testing of CFRP panels, where failure onset and propagation are captured and compared to Crain's predictions (Zhang & Yang, 2013).

3.5 Application Demonstration

Case studies are conducted on aerospace wing stringers and automotive crash structures to demonstrate the practical impact of Crain in improving prediction reliability and reducing simulation time.

4. Expected Outcomes

The Crain framework is expected to deliver:

- A validated tool for real-time, multi-scale failure prediction in composites.
- Significant improvements in accuracy and computational efficiency compared to existing methods.
- Practical applicability in aerospace and automotive safety design.

5. Conclusion

Crain addresses a critical challenge in mechanical engineering: predicting composite failure across scales under dynamic loads. By integrating microstructural modeling, reduced-order simulation, and experimental validation, Crain represents a pathway toward safer, more efficient structural design. Its application in aerospace and automotive industries promises lighter, stronger, and more crash-resistant systems.

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