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Graph Neural Networks for Efficient Prediction of Mechanical Response in Composite Structures with Models using Unstructured Meshes

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Abstract

The aviation industry is a major contributor of CO2 emissions, posing a critical challenge in the pursuit of sustainability [1]. This drive for sustainability is spurring novel aircraft configurations, particularly those incorporating alternative fuels, which requires a fundamental shift in design methodologies and techniques demanding high-performance predictive models of full-scale aircraft structures.

Finite Element Analysis (FEA) is a trusted approach for solving problems involving partial differential equations; however, it faces limitations in scalability and computational efficiency in large-scale applications, particularly in scenarios where multiple configurations require individual simulations and remeshing, leading to significant computational cost [2].

Machine Learning offers a promising avenue to accelerate structural simulations, bypassing some of FEA's computational bottlenecks. However, traditional Convolutional Neural Networks (CNNs) struggle with unstructured domains due to their reliance on regular grid representations [3], making them unsuitable for irregular meshes or complex geometries.

Graph Neural Networks (GNNs) overcome the limitations of CNNs by processing data on graphs, inherently capturing physical interactions via graph adjacencies and remaining resolution-independent [4], making them ready for handling complex and evolving geometries early in the design process.

GNNs have been used to predict the mechanical response of structural components [5], but so far accuracy for severe stress values and scalability to larger composite structures remains lacking. In this work, we developed a GNN architecture based on message passing to predict stress fields in composite structures. Our dataset consists of open hole Carbon Fiber Reinforced Polymer (CFRP) laminate plates with varying geometries and boundary conditions. The workflow involves generating field variables through a finite element solver, embedding the FE mesh into a graph, and training the GNN model on the generated dataset. The GNN architecture comprises multiple Transformer Convolutional Layers with residual connections for encoding and message passing, with resulting stress predictions are generated through a Multi Layer Perceptron (MLP) decoder that operates on the concatenation of the latent vector and the global parameters. The model can effectively predict stress fields across unexplored configurations in just 0.5% of the time of a corresponding conventional FE simulation while remaining resolution independent. At the conference, we will show various additional examples including larger structural applications with clear aerospace relevance.

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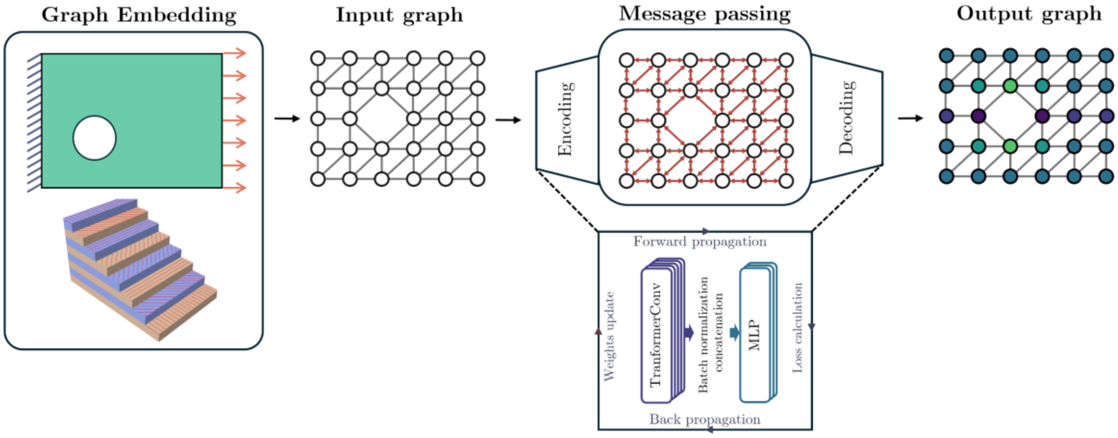

Figure 1: Workflow of the GNN model for predicting stress fields in composite structures. The process involves graph embedding of the FE mesh, message passing through multiple TransformerConv layers with residual connections, and stress prediction via an MLP decoder.

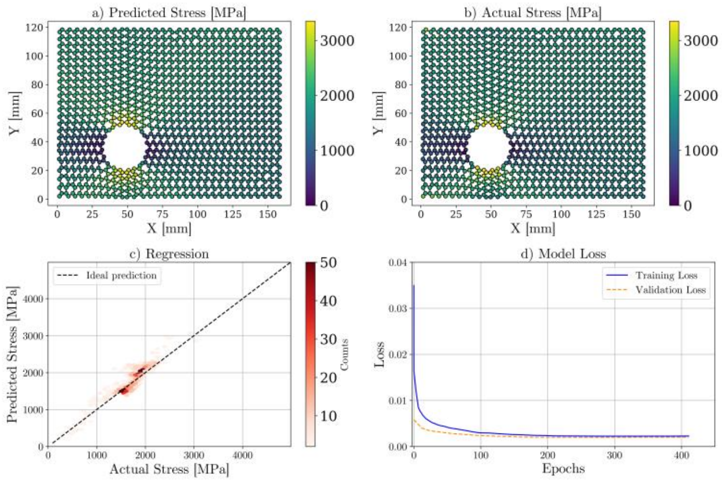

Figure 2: Evaluation of the GNN model on a CFRP composite laminate plate with an open hole. (a) Predicted stress distribution. (b) Actual stress distribution obtained from the finite element analysis. (c) Regression plot comparing predicted and actual stresses, with the line indicating ideal predictions. (d) Training and validation loss curves showing model convergence.

References

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