Machine Learning Applied to Biaxial Failure Envelope Prediction of Unidirectional Composites

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Objectives

- Investigate suitability of machine learning as an alternative to analytical failure theories to predict failure envelopes of unidirectional composite laminas.
- Predict failure under combinations of normal and shear loading at different biaxial ratios.
- Compare performance of supervised regression learning algorithms, namely, artificial neural networks, linear regression models, regression trees, Gaussian process regression models, and support vector machines on predicting composite failure.
- Train and test ML algorithms utilizing data from experimental sources for glass and carbon fiber-reinforced epoxies.

Introduction

- Composites are heterogeneous mixtures of two or more homogeneous phases. Fibers are embedded in a polymer matrix to obtain a lamina. Fibers provide strength, while the matrix holds the fibers together and transmits load among fibers.
- Composites offer mechanical properties that are highly mass efficient, thus making them popular in aerospace, wind energy, automobile, recreation industry.
- However, due to anisotropic nature of composites, failure prediction is challenging. Highly nonlinear nature of material failure is the principal reason behind the relatively slower pace of progression in this field.
- Failure occurs in two primary modes in a composite lamina - fibers may fail by rupture in tension and kink/buckle in compression, while the matrix may fail due to loads transverse to the fibers.
- Failure envelopes indicate the region of safe operation for a structure - inside the boundaries of the envelope the structure is considered safe, whereas stress-state lying on the boundary or beyond indicates failure. Such envelopes originate from failure criteria.
- To develop a failure criterion, ideally, a sound mechanistic (physical) and mathematical foundation is required, which is then informed by experimental observations to discriminate between safe and failed zones of operation.
- Composite material failure prediction is still an unresolved issue and the research community is actively pursuing failure theories that satisfy the observations from experiments.
- As an alternative to developing analytical failure theories, a top-down approach could be taken employing a machine learning tool that will learn from the failure envelope of an example material and will predict the failure surface of test materials in the same class as the example, e.g., ductile or brittle class for isotropic materials.

Machine Learning Algorithms Used

Supervised, regressive ML algorithms as implemented in MATLAB are used in this work to predict failure envelopes of composite materials. Supervised learning algorithms were selected since outputs are known to a set of input data (training data) and upon training, prediction of responses to new data are required. Regression models were selected since continuous responses are required.

- Artificial Neural Networks (ANNs)
- Linear Regression Models
- Regression Trees
- Support Vector Machines (SVMs)
- Gaussian Process Regression (GPR) Models

Problem Setup

- The input and the output definitions for the failure predicting ML algorithms are presented graphically in Figure 1. The models are provided with only one input and only one output is requested from them.
- The input of the model is the angle between the stress components applied and the requested output is the length of the failure vector from the origin to the failure surface.
- The following pre-processing was performed to the data - the normal (tensile and compressive) and the shear stresses were scaled using the normal strength (tensile and compressive) and the shear strength values respectively for that material. Upon scaling, the normal stresses ranged between -1 to 1 and the shear stresses ranged between 0 and 1.

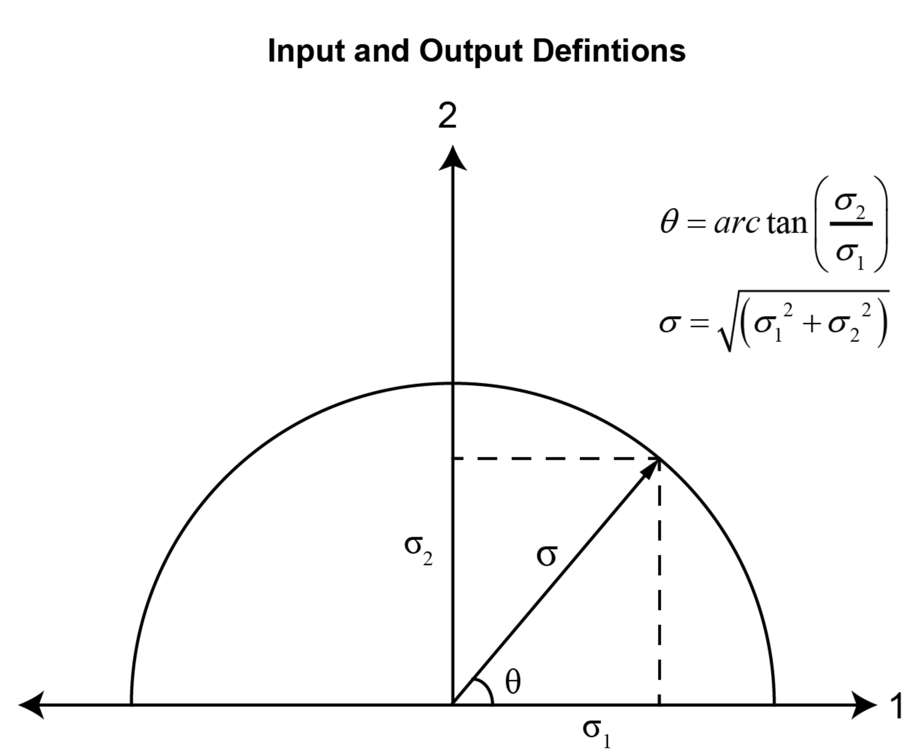

Figure 1: Schematic of the input and output definitions of the machine learning models.

Training and Testing

- The ML models were trained and tested with composite failure data set provided in WWFE program [1] and other sources [2].
- ML analysis of two cases of biaxial failure surfaces were performed in this work - (i) σ_{11} vs. τ_{12} case and (ii) σ_{22} vs. τ_{12} case.

Training and Testing (cont.)

- A cross-validation training scheme was selected to prevent overfitting the models. Holdout validation with a composition of 70% training data and 30% test data was used.
- A comparative study of the experimental data points, ML algorithm predictions, and the predictions made by a tensor polynomial failure criterion (Tsai-Wu) are presented here to evaluate the performance of the ML models.

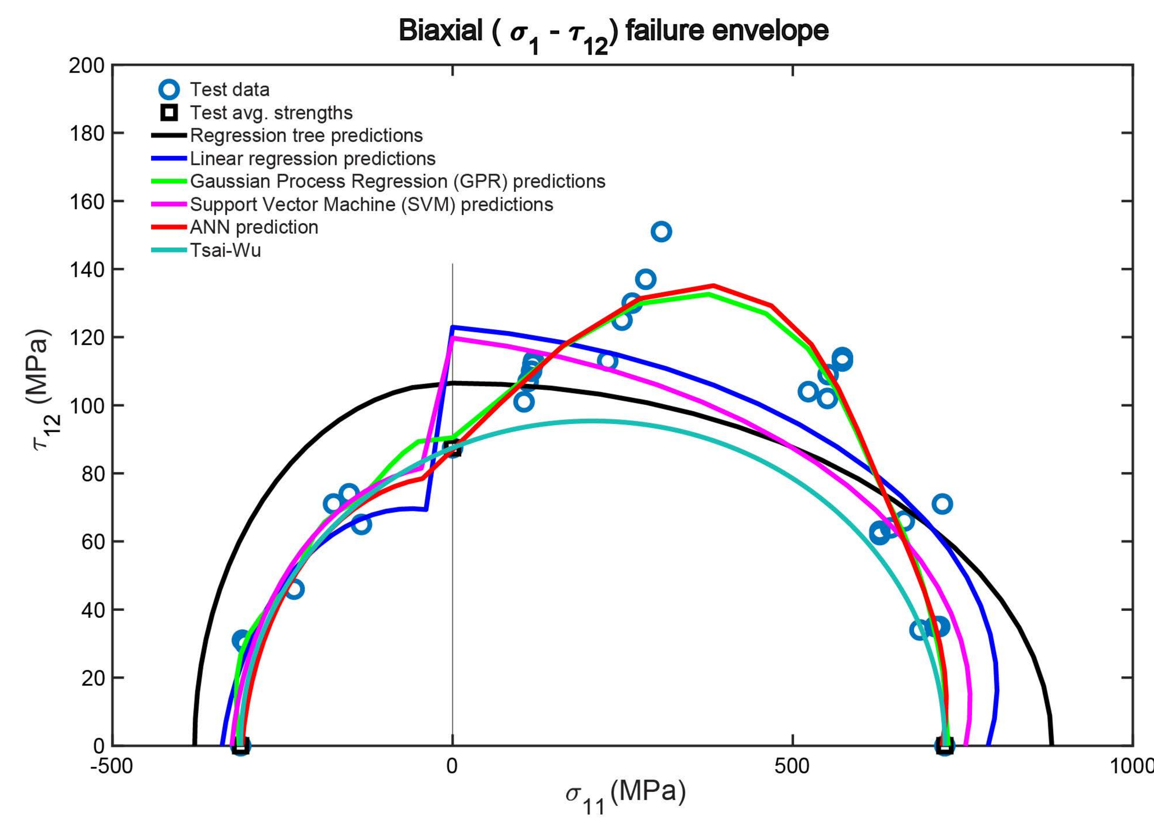

Figure 2: Biaxial failure envelopes for 0° unidirectional carbon/epoxy lamina under normal and shear loading (σ_{11} vs. τ_{12}).

- The root-mean-squared error (RMSE) of the validation data set was utilized as a performance metric of the ML models.

ML Algorithm	RMSE Case 1	RMSE Case 2
Linear Regression	0.1808	0.0686
Fine Regression Tree	0.2551	0.1708
Fine Gaussian SVM	0.0975	0.1907
Matern 5/2 Gaussian Process Regression	0.1021	0.1112
1-3-1 Artificial Neural Network	0.0737	0.0792

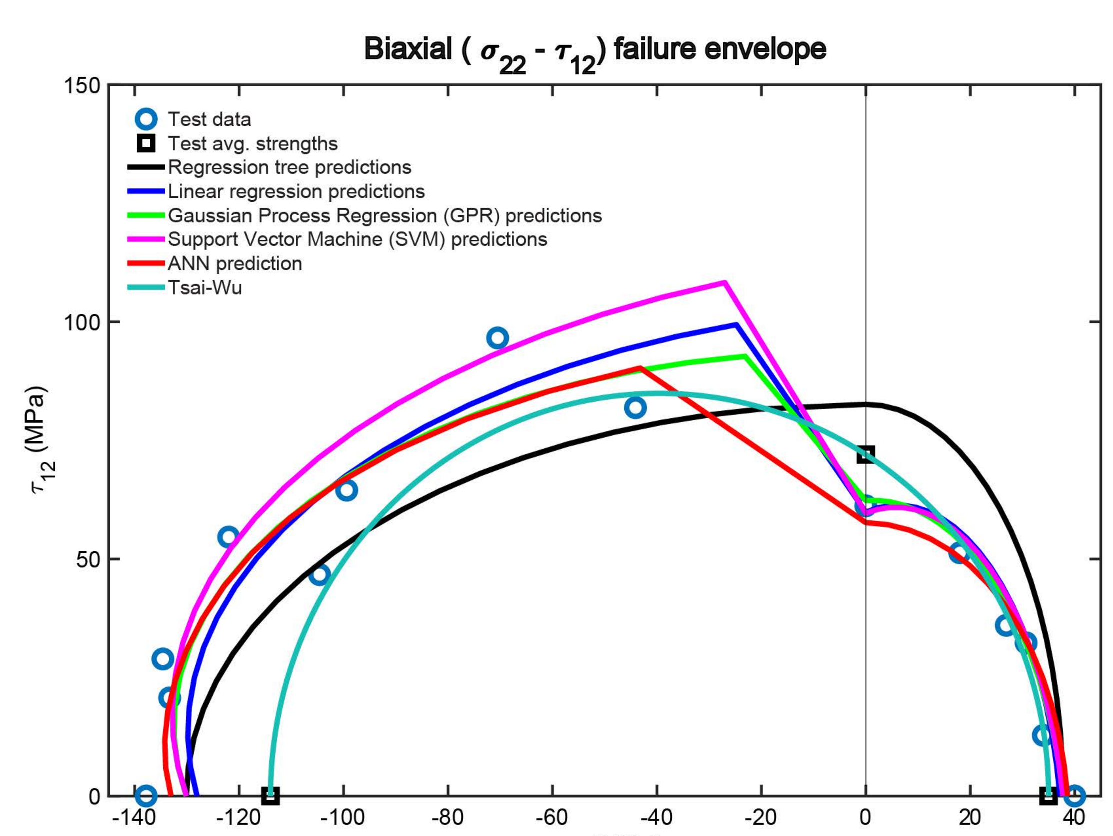

Figure 3: Biaxial failure envelopes for 0° unidirectional glass/epoxy lamina under transverse normal and shear loading (σ_{22} vs. τ_{12}).

Trained Model as Failure Criterion

- ML models trained to predict the σ_{11} vs. τ_{12} failure envelope of carbon/epoxy composite described in the foregoing section were used as traditional failure theories, i.e., failure envelope of a different carbon/epoxy material was constructed based on only the uniaxial strength information.

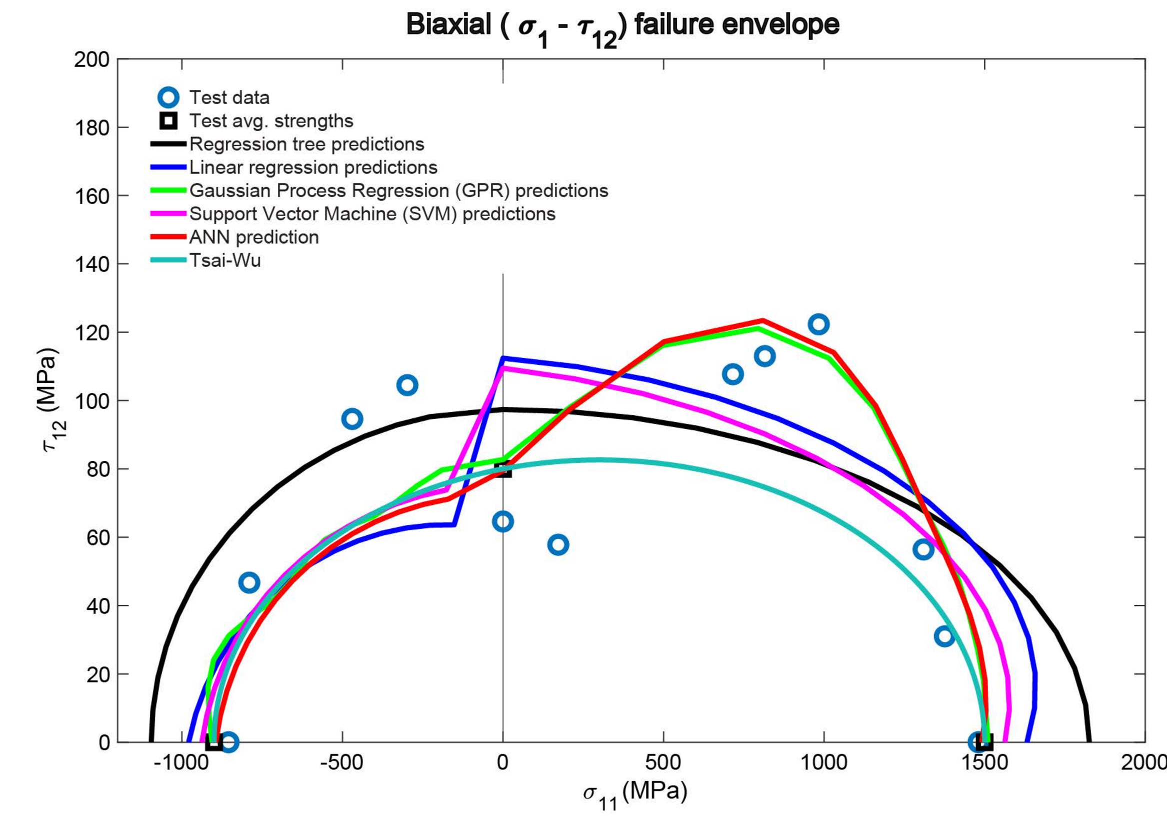

Figure 4: ML algorithms as failure theory to predict the failure contour for the 0° unidirectional lamina (for a different carbon/epoxy composite) under normal and shear loading (σ_{11} vs. τ_{12}).

Summary

- Machine learning algorithms as implemented in MATLAB were utilized to predict the failure surfaces of biaxially loaded unidirectional composite laminas.
- Five machine learning based models were designed to predict the failure envelopes, and it was observed that the RMSE for the ML predicted failure surfaces are lower than the tensor polynomial Tsai-Wu failure theory.
- Trained ML model can act as a failure criterion satisfactorily.

References

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- Lee, C., et al., Failure of carbon/epoxy composite tubes under combined axial and torsional loading 1. Experimental results and prediction of biaxial strength by the use of neural networks. Composites Science and Technology, 1999. 59(12): p. 1779-1788.

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