Artificial Intelligence Assisted Prognostic Health Monitoring of Polymer Composites

Das, Partha Pratim[1,2]; Supervisors: Vadlamudi, Vamsee[2]; Raihan, Rassel[1,2]

[1]Mechanical and Aerospace Engineering, The University of Texas at Arlington; [2]Institute for Predictive Performance Methodologies, UT Arlington Research Institute

Mechanical Engineering Graduate Research Project

Executive Summary

- A novel ANN-based prediction framework is presented in this work to predict the life and residual strength of polymer composites under fatigue loading.
- The framework incorporates in-situ dielectric data acquired from Dielectric Spectroscopy and stiffness degradation monitored through Fiber Optic Sensors.
- The prediction framework consists of two coupled ANN-based multilayer perceptron models that can predict the life and residual strength (RS) of the composite part with high accuracy.
- This study highlights the effectiveness of using in-situ dielectric permittivity data and FOS-based FBGs to improve the prediction of the life and residual strength of composite parts under fatigue loading.

Background

- Fiber-reinforced polymer (FRP) composite structures are widely used in Aerospace industries but have unpredictable damage progression and failure behavior under fatigue loading.
- Characteristic Damage State (CDS) is an indicator for severe damage, leading to stiffness degradation, but not necessarily loss of strength. (Figure 1)
- Traditional maintenance approaches are becoming obsolete, and artificial intelligence (AI) based predictive models can be trained to identify damage precursors from extensive sensor data throughout the service life of a composite.
- Different AI models have been developed, but ANN-based algorithms have been more efficient and accurate for modeling damage and prognostics [2].
- Dielectric state variables, analyzed using the Dielectric Spectroscopy (DS) technique, can be used as in-situ indicators of damage development during fatigue and coupled with ANN architecture for Prognostic Health Monitoring.

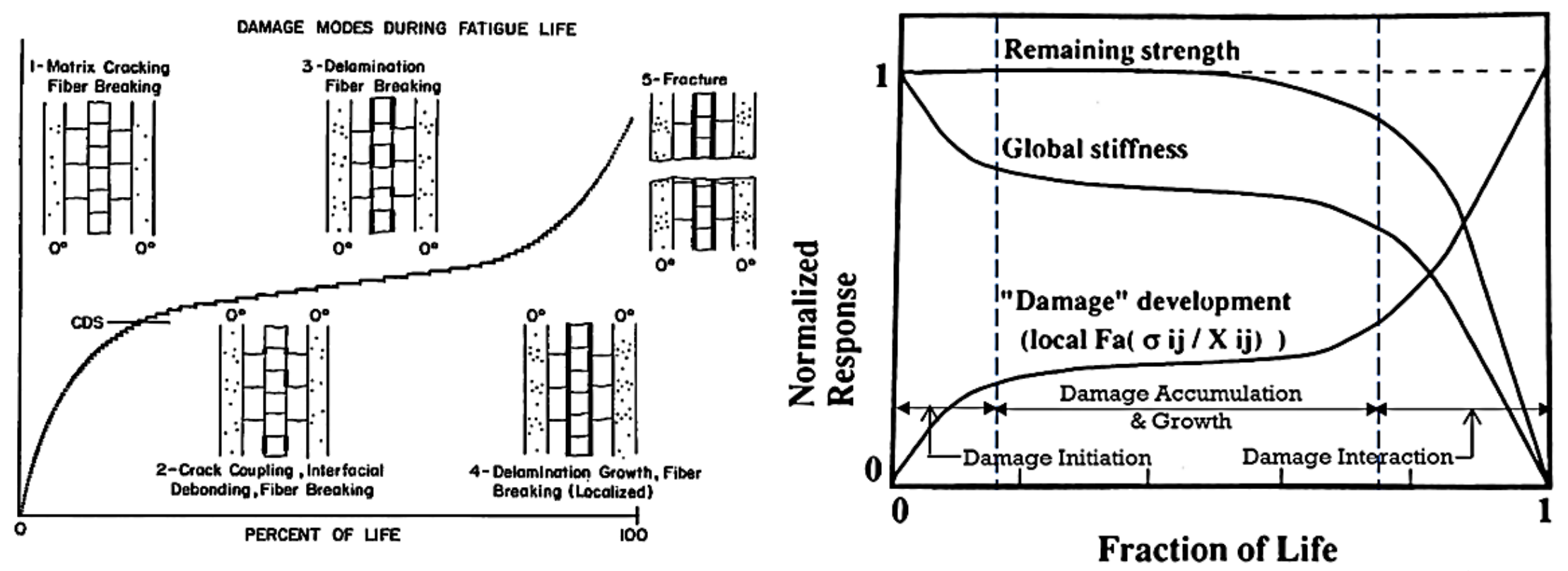

Figure 1. Damage progression in composites and relation of remaining strength, global stiffness with life [1]

Experimental Design

A. Test Material Preparation

- Composite laminates were made using unidirectional epoxy impregnated E-glass fiber prepregs with a quasi-isotropic laminate stacking sequence.
- The out-of-autoclave manufacturing process was used to cure the laminates at 135°C

B. Experimental Design

- Specimens were subjected to quasi-static tensile loading to determine the mean ultimate tensile strength (UTS).
- Fatigue tests with in-situ dielectric spectroscopy were carried out up to failure for mean stress levels (25%, 50%, and 75% of UTS) to develop a life prediction model.
- A training dataset was generated for residual strength prediction from fatigue tests for a 50% mean stress level up to predefined cycle counts.

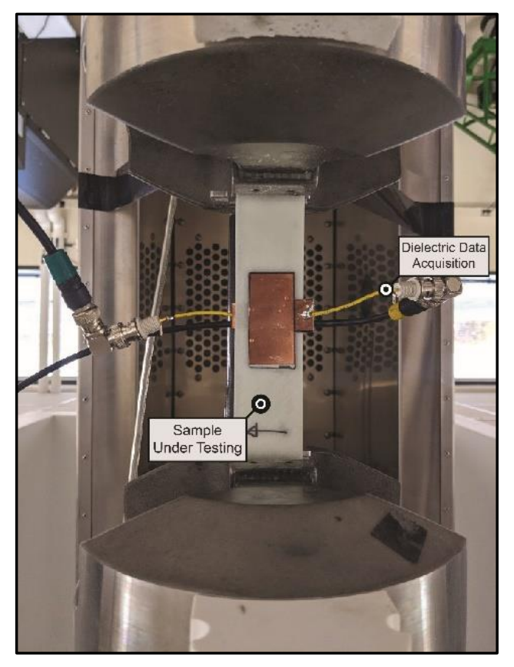

Figure 2. Test Setup

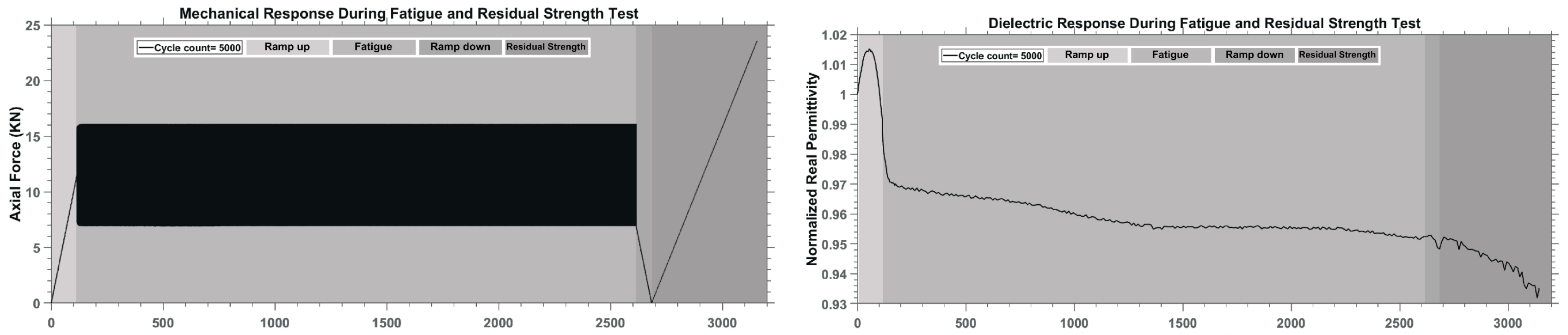

Figure 3. Mechanical Response and Dielectric Response of Composite

Analysis of Material State Variables

- Stiffness degradation and dielectric evolution shows similar pattern as reported in literature. [3]
- The acceleration of mechanical and dielectric state variables following a similar trend until about 50% of life.
- The second inflection point in the acceleration curves indicates that the dielectric response provides an earlier warning of the beginning of material failure than the mechanical response.
- The average life percentage and number of cycles based on permittivity were 68.78% and 53655, respectively, and based on stiffness, they were 71.74% and 59669, respectively.

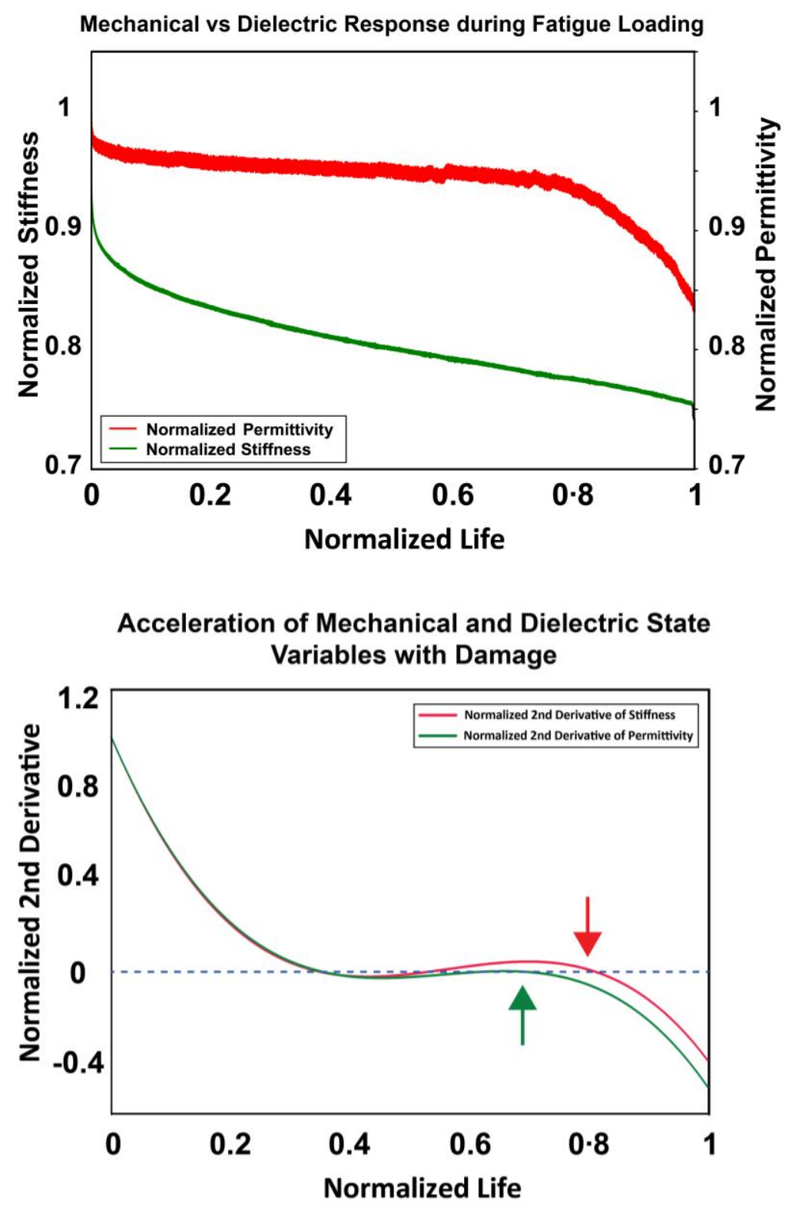

Figure 4. Analysis of State Variables

Data Curation and Model Development

- Acquired dielectric and life data is divided into finite timesteps (Figure 4)
- Two training datasets curated for Life and RS ANN Models (ANN_1 and ANN_2)
- Grid search cross-validation technique was used to find optimal hyperparameters for the models (Table 1 and 2)

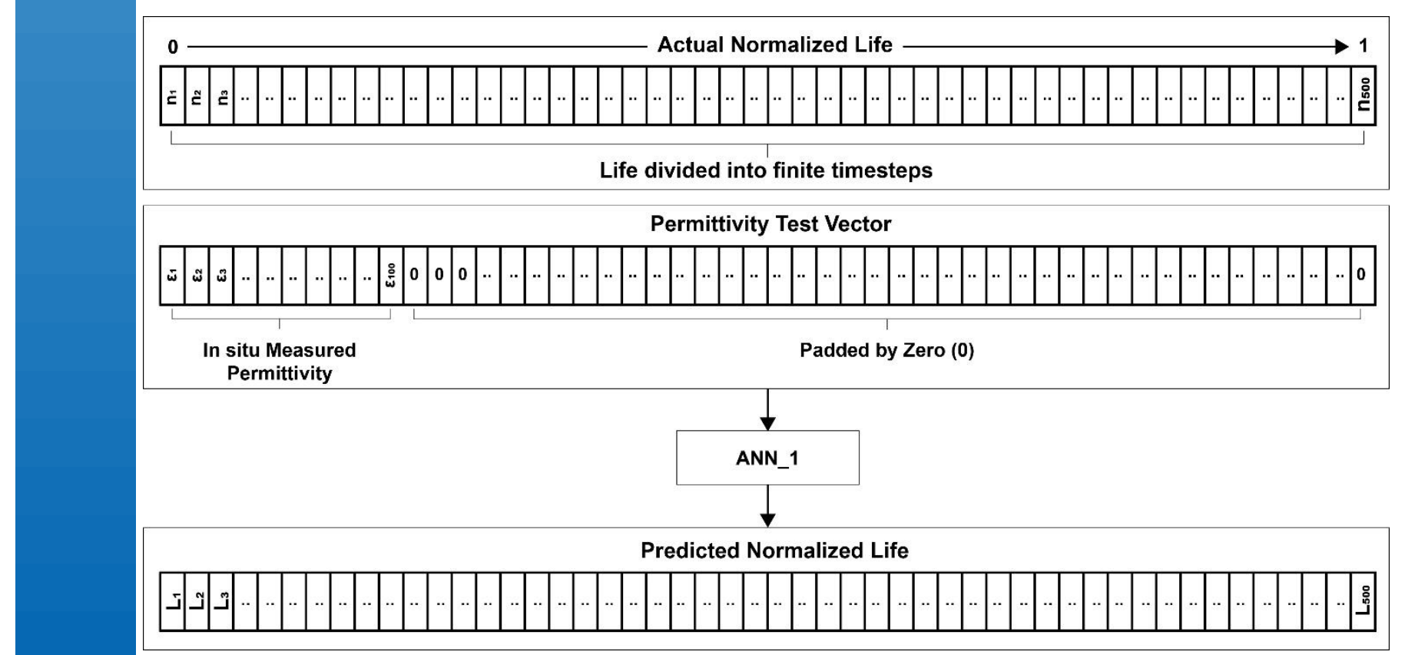

Figure 5. Data Curation Methodology

Table 1. Tuned hyperparameters for the life prediction model

Hidden Layer Sizes	Activation Function	Solver	Learning Rate	Maximum Iterations
900, 200, 800	ReLU	Adam	0.0001	5000

Table 2. Tuned hyperparameters for the RS prediction model

Hidden Layer Sizes	Activation Function	Solver	Learning Rate	Maximum Iterations
58,30,77	ReLU	LBFGS	0.00011	5000

Prediction Performance

- The framework consists of two coupled ANN models to estimate the current life (ANN_1) and residual strength (ANN_2) of the specimen based on dielectric permittivity response.
- ANN_1 provides full life prediction for test specimens from dielectric data of predefined limited cycles with average R^2 value 0.9326.
- Performance enhances when more dielectric data is available.
- The output estimated life is then passed through the ANN_2 model, and the model predicts the residual life of the specimen.
- ANN_2 predicts the residual strength with an R^2 value of 0.9613.
- The in situ dielectric permittivity response can be used to determine the present residual strength of a fatigue specimen using this coupled ANN framework.

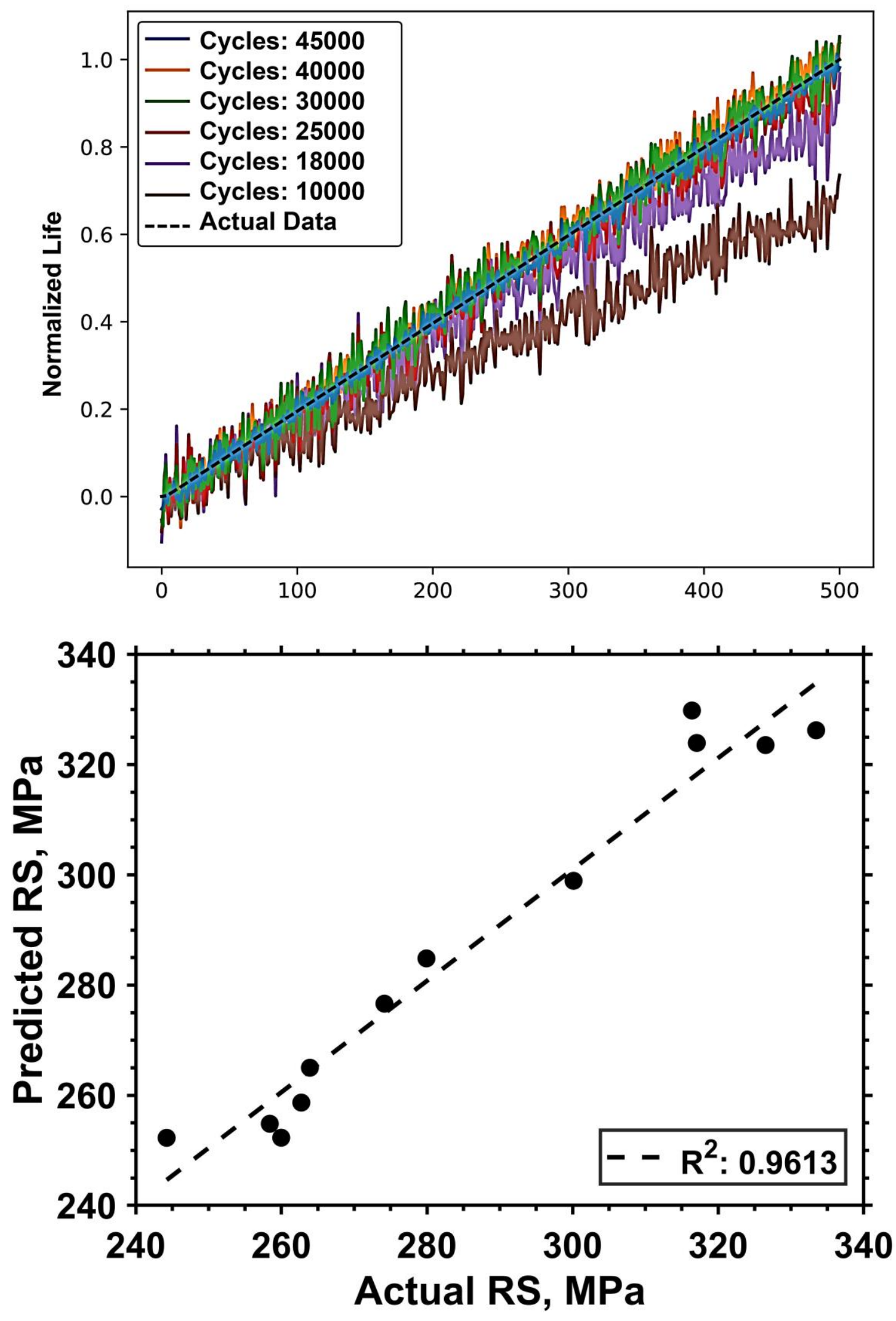

Figure 6. Model Performance

(Top: ANN_1, Bottom: ANN_2)

Conclusions and Core Findings

- Dielectric permittivity changes can be correlated with the initiation and propagation of damage in the material.
- A novel framework using artificial neural network algorithms to predict life and residual strength of polymer composites under fatigue loading is developed (Figure 7).
- Life prediction model can predict current and future life span from dielectric permittivity with high accuracy.
- The coupled framework can predict residual strength of a specimen with high accuracy
- Optimizing statistical data curation techniques and using deep neural network-based algorithms can improve the method in future studies.

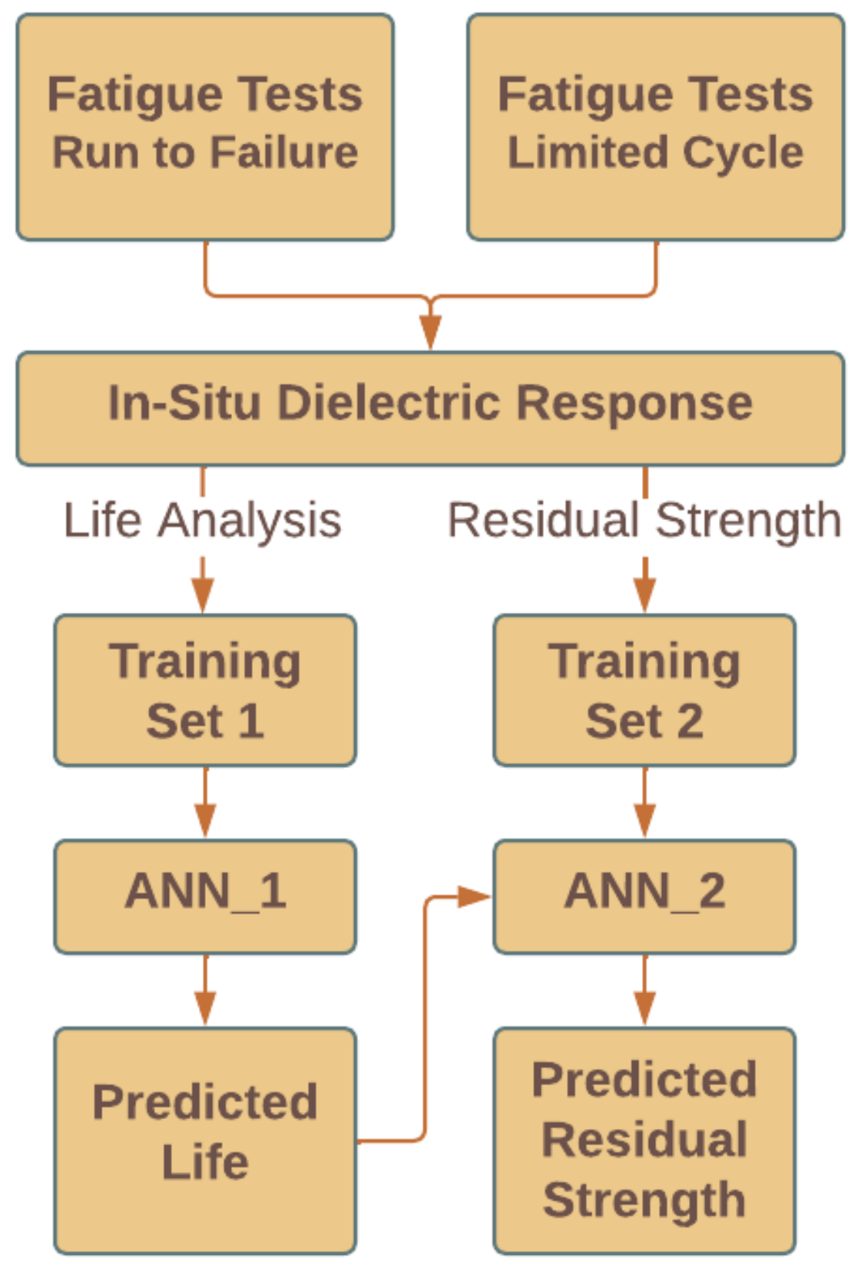

Figure 7. Proposed Prediction Framework

References

1. Raihan, R., Adkins, J.-M., Baker, J., Rabbi, F., and Reifsnider, K. Relationship of Dielectric Property Change to Composite Material State Degradation. 2014.
2. Das, P. P., Elenchezhian, M., Vadlamudi, V., & Raihan, R. (2023). Artificial Intelligence Assisted Residual Strength and Life Prediction of Fiber Reinforced Polymer Composites. In AIAA SCITECH 2023 Forum (p. 0773).
3. Elenchezhian, M. R. P. (2021). Real-time Material State Assessment of Composites Using Artificial Intelligence and Its Challenges (Doctoral dissertation).

Acknowledgements

We would like to acknowledge and thank the scholars and the staff at the Institute for Predictive Performance Methodologies at the University of Texas at Arlington Research Institute for their tremendous support of this research work.

Material State Awareness and Sustainability Lab

Institute for Predictive Performance Methodologies

UNIVERSITY OF TEXAS AT ARLINGTON RESEARCH INSTITUTE