A Neural Network Framework for Predicting Durability and Damage Tolerance of Polymer Composites under Combined Hygrothermal-mechanical Loading

Partha Pratim Das[1]

[1] *University of Texas at Arlington, TX 76019*

parthapratim.das@mavs.uta.edu

ABSTRACT

Fiber-reinforced polymer (FRP) composites are used in crucial structures which are susceptible to a combination of mechanical (static/dynamic) and hygrothermal (moisture absorption and temperature) loads. This research presents a novel artificial neural network (ANN) framework that employs the dielectric permittivity response of FRP composites under combined mechanical-hygrothermal loading to predict the extent of moisture absorption, fatigue life, and remaining useful life. The proposed framework is based on the phenomenological and data-driven study of the effects of static and dynamic mechanical loads along with moisture absorption in the dielectric characteristics of these composites.

1. INTRODUCTION

The exceptional properties of fiber-reinforced polymer (FRP) composites, such as their corrosion resistance, high strength-to-weight ratio, stiffness, fatigue endurance, and insulation capabilities, have positioned them as a formidable rival to conventional materials like metals and alloys. This has resulted in their increasing use in various structures employed in the aerospace, marine, and transportation industries. The uncertain nature of damage development, progression, and sudden failure is a weakness of FRP composites. In addition to the mechanical damage progression in FRP composites, exposure to environmental stressors such as moisture (hygrothermal loading), UV rays, and temperature fluctuations can result in damage phenomena such as plasticization, chain scission, oxidation, micro-crack development, and interfacial debonding (Stewart & Douglas, 2012). These can adversely impact the material's mechanical strength. Different structural health monitoring technologies are already in practice, which can detect the mechanical damage progression in-situ, such as comparative vacuum monitoring, acousto-ultrasonics, acoustic emission, embedded fiber bragg grating sensor, imaging ultrasonics, and visual inspection. While these methods can identify damage caused by mechanical loading, they cannot detect the impact of hygrothermal effects on FRP composites.

Broadband Dielectric Spectroscopy (BbDS)/Impedance Spectroscopy is a versatile nondestructive technique that has been proven to detect damage development due to mechanical and hygrothermal loading in our previous independent studies. When a material experiences external mechanical load (such as static or dynamic) or hygrothermal exposure, the real permittivity and dielectric relaxation strength change accordingly. Therefore, these dielectric state variables can be monitored for in-situ structural health monitoring of composites. However, due to the uncertain progression of damage in composites, the utilization of predictive models based on artificial intelligence (AI) can be beneficial in detecting damage precursors by analyzing sensor data obtained throughout the composite's operational life (Elenchezhian et al., 2021). This data can be used to model robust artificial neural network (ANN) models that can predict the failure of a composite from early life dielectric evolution, aiding effective prognostic health management of crucial structures. The overarching goal of this doctoral research is to develop an ANN framework that can predict the durability (life) and damage tolerance (remaining useful life (RUL)) of FRP composites under combined dynamic mechanical-hygrothermal loading.

2. RESEARCH OBJECTIVES

The research aims to accomplish the following objectives:

- Analyze the continuous dielectric response of aerospace-grade carbon fiber reinforced composites exposed to varying moisture levels in relation to commonly used characterization techniques (e.g., gravimetric measurement). An artificial neural network (ANN) will be trained using frequency domain dielectric permittivity

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and time domain relative moisture absorption data to predict moisture absorption accurately.

- Develop a separate ANN capable of predicting the tensile and compressive strength of composites based on real-time dielectric permittivity ($\boldsymbol{\varepsilon_r'}$).
- Explore the physics behind this phenomenon to identify the frequency that contributes the most to the accuracy of the ANNs, providing a comprehensive understanding of different polarizations reflected in the dielectric response resulting from damage due to mechanical or hygrothermal loading.
- Establish an ANN framework consisting of two ANNs that can predict the failure and remaining useful life (RUL) of dry and moisture-absorbed composites under fatigue loading using the initial dielectric response.

3. BACKGROUND STUDIES

When an FRP composite is subjected to mechanical hygrothermal loading, different kind of damage is generated that changes the local and hence bulk dielectric property. In different independent research, we have established a novel correlation between the degradation and dielectric permittivity changes and developed robust neural networks for structural and prognostic health monitoring. This section provides an overview of the background studies conducted for this research.

3.1. Hygrothermal Loading

The mechanical performance of composites under adverse hygrothermal conditions is a significant research concern, given the wide range of outdoor applications. Typically, moisture can enter the composite through various mechanisms, including diffusion, capillary effect, and absorption through defects. Water molecules inside FRP composites exist in two forms: free and bound. Free water molecules can escape during the desorption phase, while bound molecules remain chemically trapped in the hydrophilic hydroxyl (–OH) or amine (–NH_2) groups in the matrix. These bound water molecules create interfaces and micro-damage through plasticization, chain scission, hydrolysis, or interfacial debonding, negatively affecting the mechanical strength of the composite (Stewart & Douglas, 2012).

As water molecules are dipole in nature, their inclusion in a polymer matrix changes the dielectric properties of the material by imposing different polarization mechanisms. BbDS is a nondestructive characterization technique that can provide information about a material regarding molecular and dipolar perturbations as well as charge transport and polarization effects across a wide frequency range (1×10^{-6} to 1×10^{12} Hz) response. Thus, BbDS can leverage the dipolar characteristics of water molecules as sensing parameters to detect changes in the material state resulting from moisture absorption.

The relationship between moisture absorption and real permittivity ($\boldsymbol{\varepsilon_r'}$) is clearly illustrated in Figure 1. As moisture is absorbed, there is a noticeable increase in the $\boldsymbol{\varepsilon_r'}$ with a well-defined correlation. During the initial phase of absorption, when the rate is high, $\boldsymbol{\varepsilon_r'}$ increases at a rapid pace. However, as the rate of absorption slows down and approaches saturation, the rate of $\boldsymbol{\varepsilon_r'}$ increase also stabilizes. This phenomenon is most noticeable in the lower frequency range, indicating the involvement of interfacial and ionic polarization resulting from the continuous absorption of moisture.

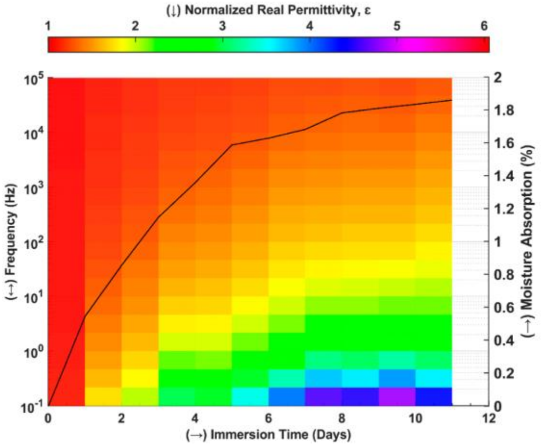

Figure 1. Heatmap of normalized real permittivity and early moisture absorption with immersion time.

This discovery led to the development of a data-driven analysis to establish a correlation between moisture absorption in composites and dielectric response. Subsequently, an ANN regression model with three hidden layers and a hyperbolic tangent activation function was trained on $\boldsymbol{\varepsilon_r'}$ response to moisture absorption. This model can accurately predict the relative moisture absorption percentage of a test specimen by analyzing the frequency domain $\boldsymbol{\varepsilon_r'}$ of the material. The hyperparameters of this model were tuned to have an R^2 value of 0.9620. The mean square error (MSE) and mean absolute error (MAE) of this model on a blind test dataset were 0.0317 and 0.1466, respectively.

3.2. Mechanical Loading

When a composite is put under static (tensile/compressive) or dynamic (fatigue) loading, damage is generated in the material that begins with the generation of matrix microcracks and progresses to a saturation phase known as the Characteristic Damage State (CDS). On continued loading, further damage can result in fiber-matrix debonding and delamination, followed by fiber failures. As the rate of interactions tends to increase, the rate of fiber failures also increases, leading to sudden and unexpected failure.

Therefore, CDS is a critical stage for monitoring as it serves as a warning of impending severe damage in composites.

The in-situ dielectric response of the material can provide insight into the damage states of composites (Vadlamudi et al., 2019). Figure 2 shows the dielectric response of an off-axis ([±45°]$_s$) composite coupon under quasi-static tensile loading. It can be seen that initially ε_r' increases and then reaches a saturation phase, followed by an initial decrease and a sharp decrease at the end. The initial increase can be attributed to the micro-crack development, while the saturation phase indicates the material has attained CDS, as evidenced by the edge replication images in Figure 2. Thus, tracking the evolution of ε_r' of the material can be used to identify the various phases of damage development.

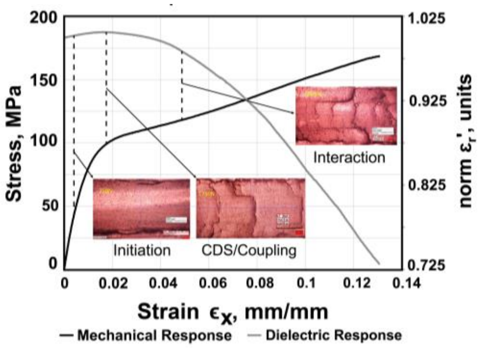

Figure 2. In situ dielectric permittivity response of a composite under quasi-static tensile loading with edge replica of different damage progression phases

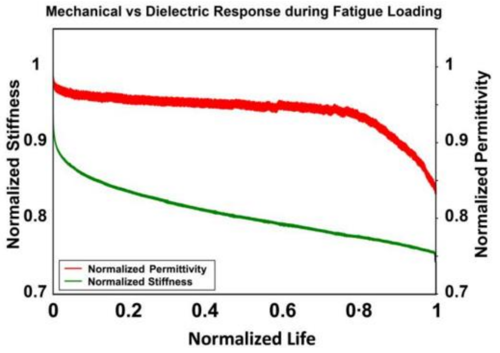

Figure 3. In situ stiffness and permittivity response over normalized life during fatigue

Fatigue is a critical loading case for a composite structure that generates different damage phases in the material, similar to quasi-static loading. In tension-tension fatigue, a cyclic load is applied to a specimen, where the upper and lower limits of the load remain within the quasi-static tensile breaking load, and the total cycle count is referred to as the 'life' of the specimen. If, after a predefined number of cycles, the specimen does not fail, it can still have some strength or 'life' left, which is referred to as the remaining useful life (RUL). During fatigue, as an FRP composite approaches CDS, its stiffness drops significantly while retaining its strength. After CDS, the stiffness degrades at a reduced rate until failure. Thus, stiffness degradation is considered an important parameter to determine the material state during fatigue.

The in-situ dielectric response and stiffness degradation of a composite specimen during fatigue is depicted in Figure 3. The figure illustrates that both stiffness and ε_r' decrease rapidly in the beginning, followed by a stable decrease rate. However, at about 75% of life ε_r' reduces at a higher pace. This significant change in ε_r' can act as an indicator of imminent failure of the material, highlighting its capability to monitor the health of composite materials subjected to fatigue.

Based on the phenomenological approach that links dielectric permittivity with damage development phases in composites, a coupled artificial neural network (ANN) framework has been developed using in-situ ε_r' data for specimens undergoing fatigue, as shown in Figure 4. This framework can estimate the current life and remaining useful life (RUL) of a test specimen and predict the cycle count at which the specimen is likely to fail. Initially, the input normalized ε_r' and cycle data (converted to normalized life) of run-to-failure specimens were curated to finite time steps of data to train the first ANN (called ***ANN_1***) for life prediction. ***ANN_1*** architecture consists of three hidden layers and an output layer of 500 nodes, with optimal hyperparameters determined using grid search cross-validation.

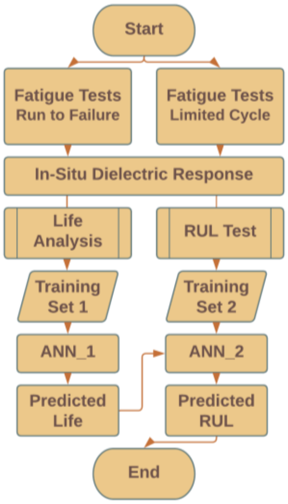

Figure 4. Developed ANN framework

The test dataset for this model consisted of dielectric data for specimens run to cycle counts within the whole fatigue life (determined from the lower 95% confidence limit using Weibull analysis). For example, if a specific specimen is expected to fail at 50,000 cycles (based on the lower 95% confidence limit), dielectric data up to limited cycle counts (i.e., 20,000 cycles) were provided to the ***ANN_1*** model. From this limited available data, ***ANN_1*** can estimate the specimen's fatigue life $n_{predicted}$ at the current state (when actual life n_{actual}: 20,000/50,000 = 0.4) and predict fatigue life at cycles greater than 20,000. Figure 5 depicts the output prediction curves for six test specimens within the whole experimental range compared to the actual data.

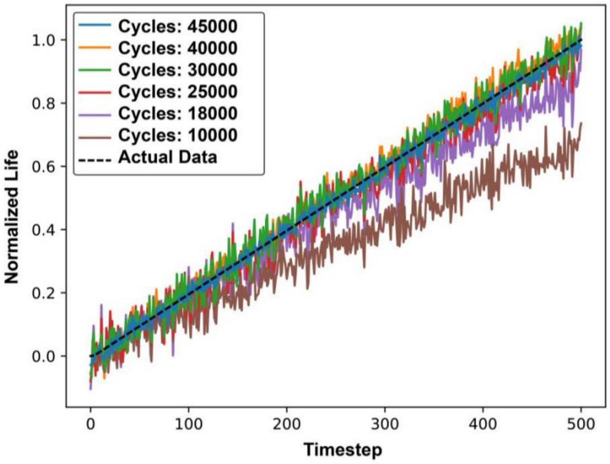

Figure 5. Prediction of fatigue life using ***ANN_1***

The developed framework (Figure 4) incorporates a second ANN (called ***ANN_2***), which is trained using the fatigue life of specimens subjected to fatigue up to a predefined number of cycles and their corresponding quasi-static RUL. ***ANN_2*** comprises three hidden layers and one output layer with a single node. The proposed framework couples ***ANN_1*** and ***ANN_2*** for RUL prediction. At first, the measured $\boldsymbol{\varepsilon}_{\mathbf{r}}'$ data for a specimen undergoing fatigue up to limited cycle counts was input into ***ANN_1*** to estimate the current fatigue life. Then, ***ANN_2*** uses the estimated fatigue life provided by ***ANN_1*** to predict RUL. The framework demonstrated reasonable accuracy in RUL prediction, with an R^2 value of 0.9613.

Thus, as per our previous studies, it has been demonstrated that with the aid of ANN-based methods, dielectric permittivity can detect hygrothermal and mechanical degradation of FRP composites with reasonable accuracy. However, in real-life scenarios, these two types of loads often occur simultaneously, and examining the competency of in-situ dielectric spectroscopy under such conditions is crucial. As such, this doctoral research aims to conduct further studies by coupling hygrothermal and mechanical loadings and develop a more reliable and effective ANN framework for prognostic health monitoring of FRP composites.

4. RESEARCH DESIGN

The following tasks have been designed to accomplish the research objectives:

- Task 1 involves conducting tensile tests on aerospace-grade FRP composites in both dry and moisture-absorbed phases while using Broadband Dielectric Spectroscopy (BbDS) to gather initial and in-situ dielectric permittivity data for both hygrothermal cases.
- Task 2 involves training an artificial neural network (ANN) using the acquired data to predict moisture absorption and tensile strength of the material.
- Task 3 involves designing fatigue experiments based on the tensile strength data of the two hygrothermal cases. This step will include conducting run-to-failure tests and limited cycle tests while acquiring in-situ dielectric data.
- Task 4 will entail training an ANN framework on the data obtained from the combined hygrothermal-fatigue experiments. This ANN will predict the fatigue life (durability) and RUL (damage tolerance) of a composite specimen undergoing both moisture absorption and dynamic loading.

A significant challenge in accurately measuring dielectric permittivity is electrode polarization, particularly at lower frequencies. Different approaches, such as modifying the surface of the electrode, optimizing the contact between the electrode and sample, and utilizing analytical methods, can be implemented to tackle the challenge. As a future work, the ANN framework can be expanded to include a wider range of material systems with varying configurations and geometries, increasing its versatility and applicability to real-world structures.

5. CONCLUSION

This research aims to develop a novel artificial neural network (ANN) framework trained from the frequency domain dielectric response of fiber-reinforced polymer (FRP) composites under combined hygrothermal-mechanical loads. The framework would be able to predict the extent of moisture absorption, fatigue life, and remaining useful life quantitively. This research will contribute to a better understanding of the damage mechanics and physical phenomena behind the degradation of composites and pave the way for the practical application of this method in real-world composite structures.

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