Fatigue Life for Mode-II Failure of Carbon Fiber Reinforced Polymer (CFRP) Composites

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This research develops a comprehensive experimental and analytical framework to predict the fatigue life of CFRP composites subjected to mode-II failure mechanisms. The investigation employs three-point bending tests on pre-preg CFRP specimens under cyclic fatigue loading, with Digital Image Correlation (DIC) systems monitoring crack propagation behavior. Experimental data from both stitched and unstitched specimens will be analyzed using Paris's Law to establish predictive relationships between crack growth rates and loading cycles. The primary objective is to integrate Paris's Law with cycle counting methodologies to create a robust predictive model for forecasting failure in CFRP composite components. This framework will provide essential insights into fatigue damage accumulation mechanisms and permit more accurate life prediction for safety-critical applications.

I. Nomenclature

P	=	force applied to center loading roller perpendicular to the plane of the specimen
δ	=	displacement of loading roller during testing perpendicular to the place of the specimen
h	=	specimen half-thickness
a_i	=	insert length in the trimmed specimen
a_0	=	delamination length at final pre-fatigue test
a_1	=	delamination length at closest measurement point
a_2	=	delamination length at furthest measurement point
r_1	=	radius of the loading roller
r_2	=	radius of the support rollers
L	=	specimen half-span
L_c	=	distance from center of support roller at cracked end to cracked end of specimen
L_u	=	distance from center of support roller at uncracked end to uncracked end of specimen
G_Q	=	candidate toughness
P_{MAX}	=	maximum applied force
a_{Pc}	=	delamination length
B	=	specimen width
C	=	compliance
m	=	compliance calibration slope
ΔK	=	stress intensity factor range

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II. Introduction

A. Purpose

In applications where parts are created with relatively small factors of safety, failure due to fatigue becomes the dominant failure mechanism. The aerospace, automotive, and wind energy industries increasingly rely on CFRP composites for structural applications where weight reduction is critical. However, these components are subjected to repeated loading cycles throughout their service life, making fatigue behavior a primary concern for design and safety.

Mode-II delamination, characterized by in-plane shear loading, represents one of the most common and critical failure modes in laminated composite structures. Despite its importance, the fatigue life prediction for mode-II failure in CFRP composites remains an area requiring significant research and development. The lack of comprehensive predictive models creates challenges for engineers attempting to design safe, reliable composite structures while maximizing performance and minimizing weight.

B. Background

Carbon Fiber Reinforced Polymer composites have become increasingly prevalent in load-bearing structural applications due to their high strength-to-weight ratio, excellent corrosion resistance, and tailorable mechanical properties. However, the anisotropic nature of these materials and their susceptibility to delamination under cyclic loading presents unique challenges for fatigue life prediction.

Mode-II interlaminar fracture occurs when adjacent plies slide relative to each other under shear loading. This failure mode is particularly relevant in composite structures subjected to bending, torsion, or impact loading. The End Notched Flexure (ENF) test has been widely adopted as the standard method for characterizing mode-II fracture toughness and studying crack propagation behavior in laminated composites [1, 2].

Paris's Law, originally developed for metallic materials, describes the relationship between crack growth rate and the stress intensity factor range during cyclic loading. The law takes the form:

$$\frac{da}{dN} = C(\Delta K)^m \tag{1}$$

where $\frac{da}{dN}$ is the crack growth rate per cycle, ΔK is the stress intensity factor range, and C and m are material constants determined experimentally. Adapting this framework to composite materials, particularly for mode-II loading, requires careful experimental characterization and validation.

C. Objectives

The primary objectives of this research project are:

- Predict the fatigue life of a CFRP composite part under mode-II fatigue loading conditions
- Perform three-point bending tests on pre-preg CFRP composite specimens under fatigue loading conditions
- Study and collect data on crack propagation in CFRP composite specimens under mode-II loading conditions
- Use Paris's Law of crack propagation along with collected data to fit an equation to predict crack growth under a known number of cycles
- Incorporate Paris's Law and a cycle counting method to predict when a CFRP composite specimen will fail
- Compare the fatigue behavior of stitched and unstitched CFRP specimens to evaluate the effect of through-thickness reinforcement

III. Experimental Work

A. Specimen Details

The experimental investigation utilizes Size 1 CFRP composite specimens in both stitched and unstitched configurations. The specimens were manufactured using pre-preg carbon fiber/epoxy material with a unidirectional layup. Each specimen features a mid-plane insert to create an initial crack for mode-II fracture testing.

The specimen dimensions are standardized according to ASTM guidelines for ENF testing [2]. The nominal specimen geometry includes:

- Length: [25 mm]
- Width (B): [25 mm]
- Thickness ($2h$): [1.8 mm]

Stitched specimens incorporate through-thickness reinforcement to evaluate the effect of stitching on delamination resistance and fatigue performance.

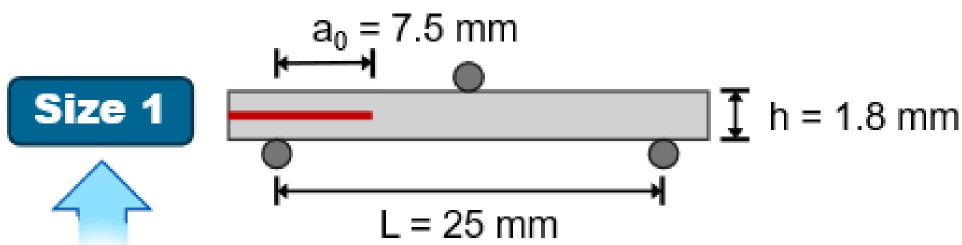


Fig. 1 Geometry of Size 1 Specimen

B. Setup

The experimental setup consists of three primary components required for comprehensive characterization of mode-II fracture behavior under both quasi-static and cyclic loading conditions.

1. Compliance Setup

The compliance testing setup utilizes the End Notched Flexure (ENF) configuration [2], which consists of a three-point bending arrangement with the specimen supported on two cylindrical rollers and loaded at the midspan by a central cylindrical roller. The test fixture is mounted in a universal testing machine capable of precise load and displacement control.

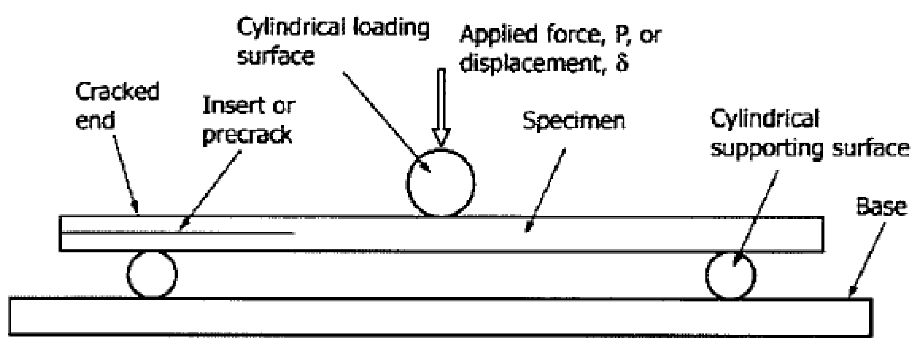


Fig. 2 ENF Test Fixture and Specimen Nomenclature

Compliance testing is performed to establish the relationship between specimen compliance and crack length, which is essential for subsequent fracture toughness calculations and fatigue testing. The compliance (C) is defined as the ratio of displacement to load:

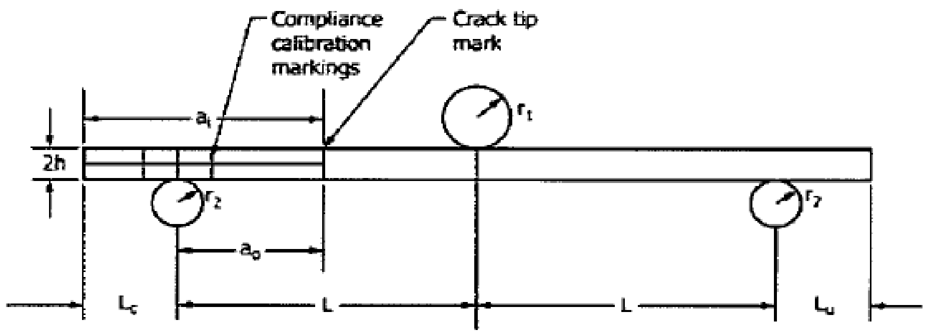


Fig. 3 ENF Specimen, Fixture and Dimensions

$$C = \frac{\delta}{P} \tag{2}$$

The compliance calibration procedure [2] involves testing specimens at multiple crack lengths. For this investigation, three distinct crack lengths were evaluated:

- a_2: The furthest measurement point, representing the longest crack length evaluated
- a_1: The closest measurement point, representing the shortest crack length
- a_0: The final test configuration before preparing the specimen for fatigue loading

The compliance load is calculated from the softening load observed during quasi-static loading. The softening load represents the point at which crack propagation begins, indicated by a deviation from linear load-displacement behavior. For each crack length (a_0, a_1, a_2), the corresponding compliance values are recorded and used to develop a compliance calibration curve.

The compliance calibration method enables determination of the crack length during fatigue testing through periodic compliance measurements, eliminating the need for continuous visual monitoring. This relationship is expressed as:

$$C = f(a) \tag{3}$$

where the functional form is determined through curve fitting of the experimental compliance data.

The candidate toughness for mode-II fracture is calculated using [2]:

$$G_Q = \frac{3mP_{MAX}^2 a_{Pc}^2}{2B} \tag{4}$$

where m is the compliance calibration slope obtained from the plot of $C^{1/3}$ versus crack length.

2. Digital Image Correlation Setup

The Digital Image Correlation (DIC) imaging system consists of four primary components that enable real-time monitoring of crack propagation during fatigue testing.

The first component involves setting up the camera used to capture images throughout the test duration. The camera is connected directly to the computer system, allowing real-time visualization of the specimen as adjustments are made to optimize image quality. The camera is positioned to capture the region extending from the specimen midspan to the center loading roller, ensuring complete coverage of the crack propagation zone.

Following camera positioning, the lighting setup is completed to ensure adequate visibility of the surface features. Two small LED lights are placed in line with the specimen to illuminate the speckle pattern applied to the specimen surface. Proper lighting is critical for accurate DIC analysis, as insufficient contrast or uneven illumination can compromise the correlation algorithms. Once the specimen is adequately illuminated and the speckle pattern is clearly visible, two test images are captured and processed through calibration software to verify image quality and system readiness.

3. *Fatigue Testing Setup*

The fatigue test integration with DIC monitoring begins by configuring the boundary conditions in the LabVIEW Virtual Instrument (VI) used for compliance testing. The VI is programmed to acquire data at a rate of 40 samples per second, while the DIC system is synchronized to capture an image every 440 samples. This imaging frequency ensures sufficient temporal resolution to track crack growth while managing data storage requirements.

The fatigue testing machine is configured to apply sinusoidal cyclic loading with an amplitude determined from previously measured calibration values specific to each specimen type. The load amplitude, measured in newtons, is selected to achieve the desired stress intensity factor range for the test. A designated file path is established to save the calculated values from the fatigue test directly to the computer system.

The VI records data in blocks of 400 cycles, saving each block sequentially to enable monitoring of test progress without interruption. The fatigue test continues until the specimen displacement increases by 0.26 millimeters relative to the initial displacement value. This displacement criterion corresponds to significant crack propagation, indicating that the crack has approached the center roller position.

Upon completion of the full fatigue test, the displacement data is plotted to visualize the progression from the initial displacement to the final displacement when crack propagation reaches the center roller. This displacement history, combined with the synchronized DIC images, provides a comprehensive record of crack growth behavior throughout the fatigue life of the specimen.

IV. Results

A. Compliance Testing

The compliance testing results demonstrated a strong linear relationship between displacement cubed and compliance for all three crack lengths (a_0, a_1, a_2). Figure 4 shows the compliance calibration curve, which exhibited an R^2 value of 1.000, indicating excellent linearity and validating the suitability of the specimen for fatigue testing.

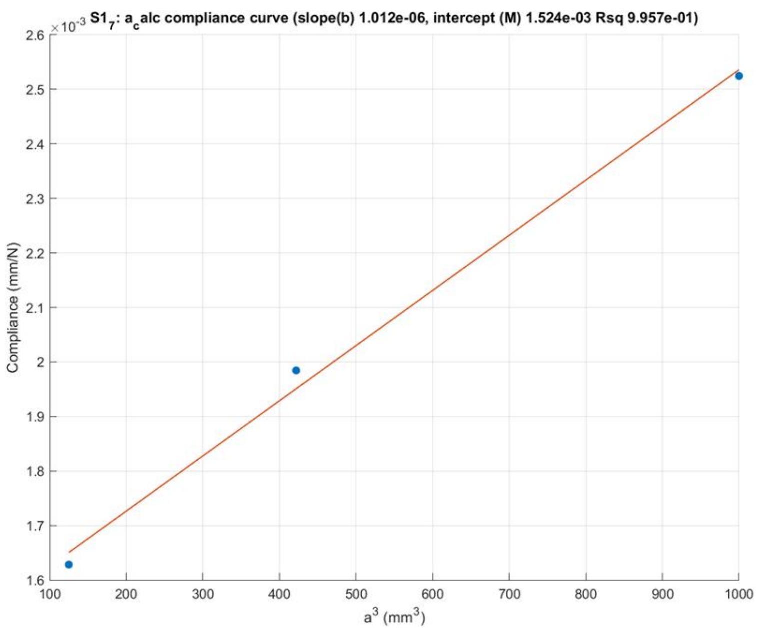


Fig. 4 Compliance as a function of displacement cubed for crack lengths a_0, a_1, and a_2.

To verify the linear elastic behavior prior to crack propagation, individual load–displacement curves for each crack length were examined. These results are shown in Figure 5, which confirms consistent elastic loading behavior across all three configurations.

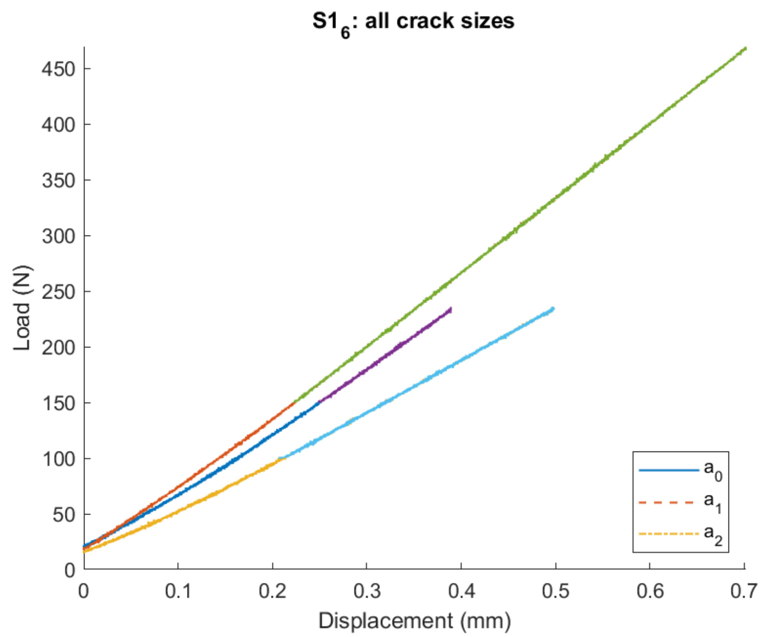


Fig. 5 Displacement vs. Load curves for each crack length configuration.

The compliance values from these tests were used to calculate fracture energy for each configuration and were subsequently implemented in the fatigue post-processing code to determine crack length as a function of cycle count.

B. Unstitched Specimen Fatigue Data

Figure 6 shows the force–displacement response over all fatigue cycles for an unstitched specimen. The curve indicates gradual permanent deformation and stiffness degradation throughout the loading history, consistent with progressive crack growth.

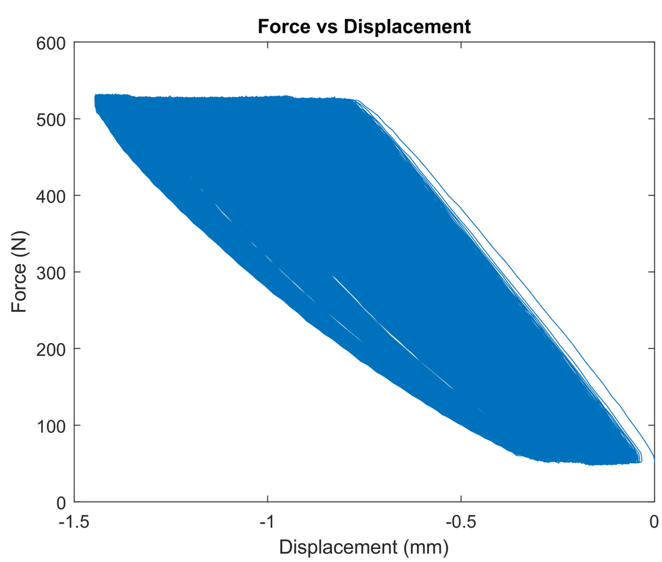


Fig. 6 Force vs. displacement response over the full fatigue test for the unstitched specimen.

Using compliance-derived crack length estimates, the crack growth rate per cycle was calculated. Figure 7 presents the resulting crack growth rate curve. Due to multiple interrupted tests and premature specimen failures, the available dataset is insufficient to establish a definitive Paris-type relationship. Testing is ongoing to support the current results.

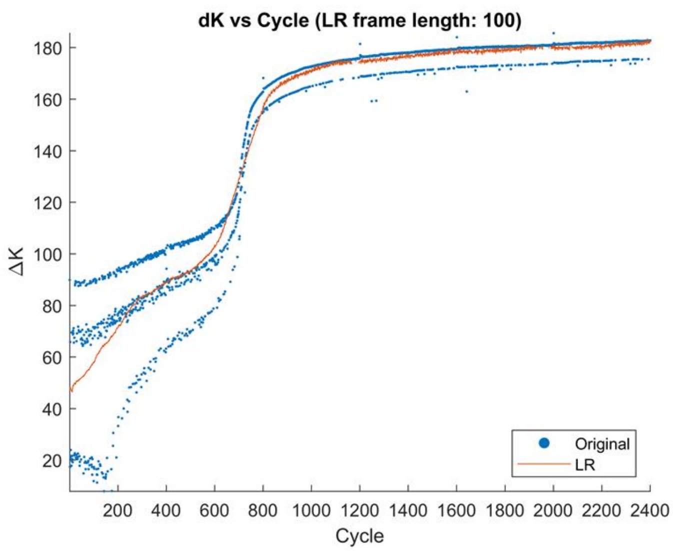
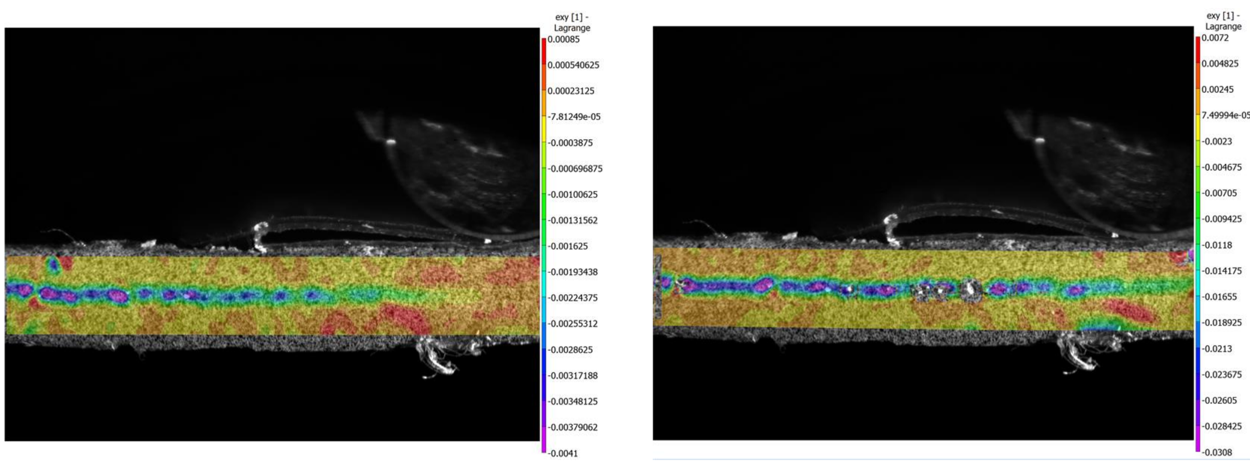


Fig. 7 Cycle vs. Stress Intensity Factor Range

Figure 7 illustrates the rate of increase for ΔK for each cycle for a unstitched specimen.



(a) Cycle 82

(b) Cycle 3316

Fig. 8 Unstitched Specimen Crack Growth

Figure 8 shows the crack length near the start of testing and at unstitched specimen failure. Failure was determined by the location of the crack under the center roller and comparing other specimens with the correlating cycle number.

C. Stitched Specimen Fatigue Data

Figure 9 shows the force–displacement response over all fatigue cycles for an unstitched specimen. The curve indicates gradual permanent deformation and stiffness degradation throughout the loading history, consistent with progressive crack growth.

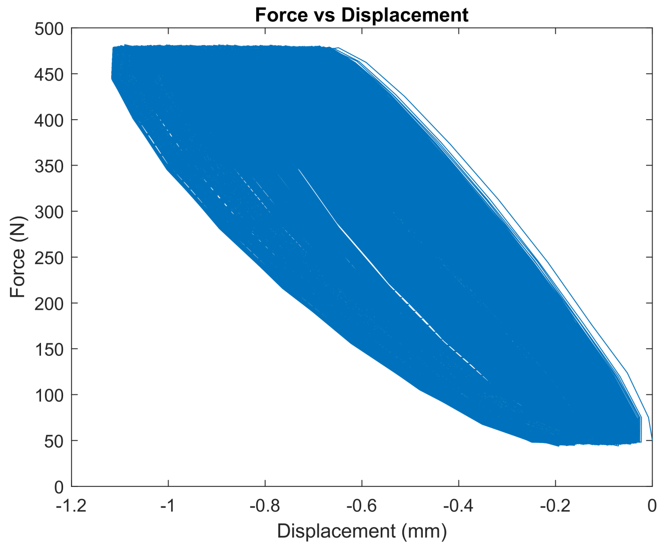


Fig. 9 Force vs. displacement response over the full fatigue test for the stitched specimen.

Using compliance-derived crack length estimates, the crack growth rate per cycle was calculated. Figure 10 presents the resulting crack growth rate curve. Due to multiple interrupted tests and premature specimen failures, the available data set is insufficient to establish a definitive Paris-type relationship. Further testing is ongoing to verify results.

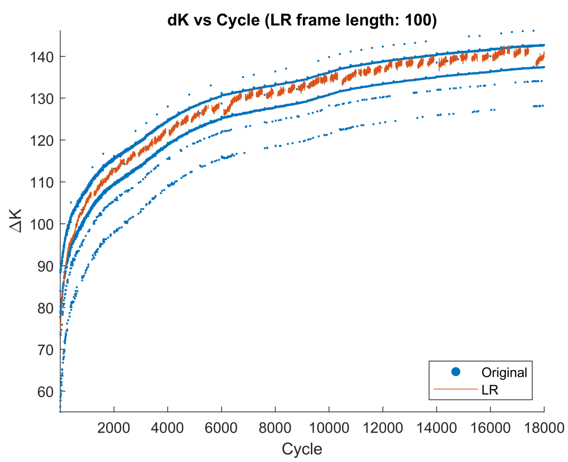
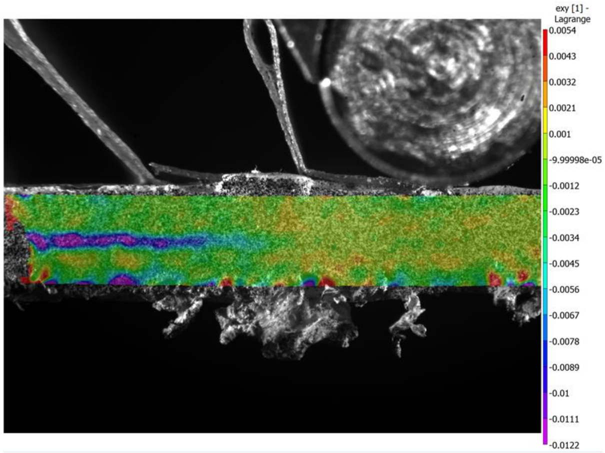
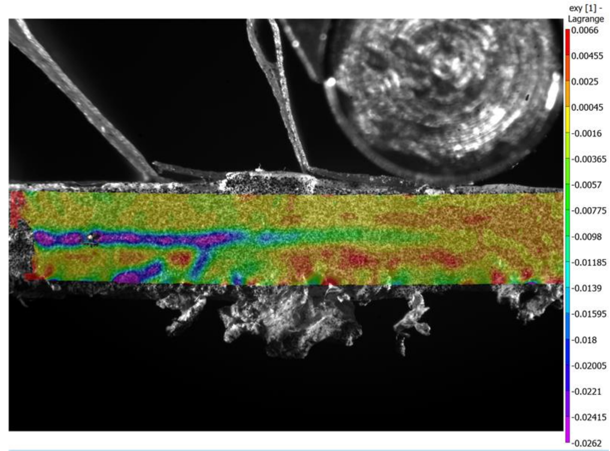


Fig. 10 Cycle vs. Stress Intensity Factor Range

Figure 10 illustrates the rate of increase for ΔK for each cycle. Due to the large number of cycles for testing the acceleration section, as seen in Figure 7, approximately between cycles 0 to 800.



(a) Cycle 82



(b) Cycle 3316

Fig. 11 Stitched Specimen Crack Growth

Figure 11 shows the crack length near the start of testing and at the failure cycle of the unstitched specimen.

V. Conclusion

This ongoing research project addresses the critical need for reliable fatigue life prediction methods for mode-II failure in CFRP composites. The experimental framework combining ENF testing, compliance calibration, and DIC monitoring provides a comprehensive approach to characterizing fatigue behavior. Preliminary compliance testing has established the foundation for subsequent fatigue analysis, with full-scale fatigue testing currently in progress. The integration of Paris's Law with experimental data will allow development of predictive models for practical engineering applications.

Acknowledgments

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References

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[2] "Standard Test Method for Determination of the Mode II Interlaminar Fracture Toughness of Unidirectional Fiber-Reinforced Polymer Matrix Composites," ASTM D7905/D7905M-19ε1, ASTM International, West Conshohocken, PA, USA, 2019, doi: 10.1520/D7905_D7905M-19E01.