



Article

Geometric Design of Dog-Bone Specimens for Accurate Fatigue Life Characterization of High-Strength CFRP Laminates

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Abstract

Tension–tension fatigue testing of polymer matrix composites (PMCs) conducted per ASTM D3479/D3479M using rectangular specimens is widely plagued by premature crack initiation and propagation at the edges of reinforcing grip tabs, which leads to severe underestimation of the material's actual fatigue life. While dog-bone specimen geometries have been universally adopted to mitigate this issue, and benchmark studies have validated their ability to completely eliminate grip-region failures in low-to-intermediate-strength PMCs, our preliminary work identified a critical unaddressed limitation: standardized dog-bone configurations produce highly unreliable fatigue characterization results for T800-grade and higher-strength carbon fiber-reinforced polymer (CFRP) laminates, with experimentally measured fatigue lives deviating significantly from predictions derived from classical laminate theory. To resolve this discrepancy and enable accurate fatigue performance quantification for high-strength CFRP laminates, the present work focuses specifically on the transition region geometry of dog-bone specimens, which we hypothesized to be the source of spurious premature failures in high-strength laminate testing. The study is bounded to tension–tension fatigue loading regimes relevant to high-performance structural applications of T800-grade and above CFRP laminates, with the core objective of developing an optimized geometry that eliminates premature non-gauge-section failures. First, statistical analysis of a large dataset of preliminary tests confirmed that transition region geometric parameters exert a non-negligible effect on the measured fatigue performance of advanced high-strength fiber-reinforced polymer laminates; stress concentrations induced by non-optimized geometries were identified as the root cause of premature non-gauge-section failures even in conventional dog bone specimens. We then systematically varied transition region geometric parameters, performed finite element stress modeling to quantify full-field stress distributions for each candidate geometry, and conducted parallel tension–tension fatigue tests on all designed configurations to cross-validate simulation outputs and experimental performance. Our results demonstrate that the optimized dog-bone configuration developed in this work completely eliminates all spurious non-gauge-section failure modes. Fatigue lives measured using the optimized geometry show excellent agreement with classical laminate theory predictions, enabling robust, repeatable quantification of the intrinsic fatigue life of high-strength CFRP laminates. The proposed configuration addresses the longstanding reliability gap associated with standardized dog-bone geometries for high-strength fiber-reinforced polymer fatigue characterization.



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Keywords: high-strength carbon fiber-reinforced polymer (CFRP) laminates; tension–tension fatigue testing; dog-bone specimen geometry optimization; stress concentration; fatigue life characterization

1. Introduction

The threshold stress intensity factor range (ΔK_{th}) is a core parameter for evaluating a material's resistance to fatigue crack propagation, and its accurate prediction is paramount to ensuring the long-term reliability and safety of engineering structures. Traditional fatigue threshold theories and testing protocols are developed almost exclusively for macroscopic specimens, rooted in the fundamental assumption that materials are continuous, homogeneous media, and that ΔK_{th} is an inherent, size-independent material constant. However, the ongoing miniaturization of engineering components, paired with advances in microstructural characterization, has challenged this assumption; mounting evidence shows that fatigue behavior, and particularly ΔK_{th} , is strongly modulated by the characteristic dimensions of both the component and its underlying microstructure. This so-called “size effect” renders conventional ΔK_{th} prediction methods unreliable for small-scale components, creating a critical gap between existing modeling frameworks and modern structural design requirements.

Early efforts to improve ΔK_{th} prediction accuracy focused on correlating threshold values to intrinsic material properties, independent of component size. Mei and Xing proposed a ΔK_{th} estimation method based on microstructural feature size and Vickers hardness, applicable to both forged and additively manufactured metals [1]; Li and Rosa systematically validated predictive models for the intrinsic fatigue threshold of metallic alloys using large experimental datasets [2]; Tanaka and Akiniwa incorporated the plasticity-induced crack closure effect into a modified strip yield model to predict the fatigue threshold of pre-cracked specimens [3]; and Li et al. modified the dual driving force model to further improve ΔK_{th} prediction accuracy [4]. As the size effect gained broader recognition, researchers turned to characterizing its underlying theoretical foundations. Kirane and Bažant (2016) conducted a systematic investigation of size effects in quasi-brittle materials based on Paris' Law and fatigue life data, proposed a modified theoretical framework, and validated it against both experimental results and microstructural models, confirming that both fatigue crack growth behavior and fatigue life exhibit non-linear size effects that cannot be fully captured by linear elastic fracture mechanics [5]. Montagnoli, Invernizzi and Carpinteri compared size effects in the Paris Law and Wöhler method from a fractal geometry perspective, noting that fatigue threshold increases with crack length while fatigue limit decreases with specimen size [6]; Carpinteri and Montagnoli further elaborated on the scaling properties and fractality of fatigue crack growth, and their impacts on Paris' Law and Wöhler curve formulations [7]. Subsequent work extended these size effect frameworks to a broad range of engineering materials, validating their real-world applicability. Aigner et al. studied the statistical size effect in cast aluminum alloys, developing a fatigue assessment model integrating a Kitagawa–Takahashi diagram and crack resistance based on the statistical distribution of defect sizes in reference and arbitrarily scaled volumes; their results showed that existing statistical size effect evaluation methods can lead to ~10% overdesign, while their proposed method reduced maximum conservative deviation to only ~5% [8]. Bai et al. proposed a method for predicting the fatigue strength of large-scale components via direct size effect measurement and characterization [9], while Qiao et al. investigated size effects and scaling laws for quasi-static and fatigue fractures in graphene polymer nanocomposites, finding that the prominent fracture process zone (FPZ)

induced by graphene nano-modification leads to a non-linear correlation between failure behavior and structural size that cannot be characterized by LEFM, but is well captured by the Size Effect Law [10]. Zhao et al. developed a multiaxial fatigue life prediction model accounting for both stress gradient and size effects [11]; Sountharajah and Kodikara verified the consistency between Bažant's Size Effect Law and flexural strength test results for cement-stabilized pavement materials using geometrically similar beams of three different sizes, and proposed a stress-based fatigue model incorporating size effects [12]; and Schönbauer and Mayer investigated the impact of small defects on the fatigue strength of martensitic stainless steels, establishing a quantitative correlation between defect size and fatigue limit [13]. Collectively, these studies confirm the ubiquity of non-linear size effects in fatigue behavior across material systems, yet most focus on either fatigue life or crack growth rate rather than the specific impact of size on ΔK_{th} prediction accuracy.

Critical knowledge gaps remain regarding the multi-scale mechanisms driving size-dependent ΔK_{th} behavior, which further limits the development of accurate predictive models. At the microscale, fatigue crack initiation and early propagation are heavily governed by microstructural features including grain size and boundaries, second-phase particles, inclusions, and micro-defect distributions. When component characteristic dimensions are comparable to these microstructural feature sizes, the homogenization assumption underpinning macroscopic mechanical theories breaks down. While crystal plasticity finite-element methods can simulate localized plastic deformation and stress/strain concentrations in polycrystalline materials under cyclic loading, and capture the influence of microstructural features on short crack growth, the resulting threshold estimates still depend on specimen or component geometry, and cannot be generalized across length scales. Short crack propagation also differs fundamentally from long crack behavior; short cracks often grow at lower applied ΔK values than long cracks, and are more strongly impeded by microstructural barriers, meaning predictions based on macroscopic long crack growth theories are inherently inaccurate for small components. At the mesoscale, damage mechanics frameworks treat the fatigue threshold as the point at which damage accumulation reaches a critical state, but damage accumulation and evolution are themselves size-dependent. For example, the density and distribution of internal defects vary across specimens or components of different sizes, leading to divergent initial damage initiation conditions and propagation pathways [14–18]. While continuum damage mechanics and multi-scale damage evolution models can describe these damage processes, their parameter calibration and applicability require re-evaluation for small-sized or thin-walled structures. At the macroscopic scale, as component dimensions decrease, the surface-to-volume ratio increases substantially [19–22], and surface effects and size-dependent defect distributions become dominant drivers of fatigue performance, altering both damage accumulation pathways and the critical damage value required for crack initiation [23].

The complexity of size effects on ΔK_{th} is further amplified under coupled loading and environmental service conditions, where existing size effect frameworks rarely account for interaction effects between external conditions and dimensional scaling [24,25]. For instance, in corrosion fatigue scenarios, the initiation and growth of corrosion pits are inherently size-dependent, where pit dimensions and morphology directly govern crack initiation locations and the resulting threshold values, introducing additional layers of non-linearity that are not captured by conventional size effect models developed for ambient, uniaxial loading conditions [26,27]. This lack of consideration for coupled condition size effects further limits the applicability of existing ΔK_{th} prediction methods to real-world structural components operating in complex service environments.

The present study aims to address the aforementioned gaps by developing a physically consistent, size-dependent fatigue threshold prediction framework applicable across

material systems, component scales, and common service conditions [28–30]. Specifically, we first quantify the multi-scale coupling mechanisms governing size effects on ΔK_{th} through systematic microstructural characterization, in situ fatigue testing, and multi-scale numerical simulation, establishing a quantitative correlation between microstructural feature size, component geometry, and threshold values [31–34]. We then integrate these multi-scale scaling relationships into a unified predictive model, with additional correction factors incorporated to account for coupled corrosion-fatigue size effects. Finally, we validate the proposed framework against independent test datasets covering metallic alloys, quasi-brittle materials [35,36], and miniaturized component fatigue tests to verify its accuracy and generalizability. This work provides a robust, widely applicable tool for accurate ΔK_{th} prediction, bridging the gap between conventional macroscopic models and the design requirements of modern miniaturized engineering structures operating under varied service conditions.

2. Materials and Methods

The experimental procedure commenced with the systematic grouping and numbering of all test specimens. Prior to testing, the dimensions of each specimen were precisely measured; a digital caliper was utilized to determine width, while a digital micrometer was employed for thickness measurements, with all data meticulously recorded. Following the dry-state dimension measurements, the specimens underwent a conditioning process. No specific requirements were imposed on the moisture content during this phase, meaning that specimen humidity was retained from manufacturing. Dry specimens were conditioned at a laboratory temperature of 23 ± 2 °C and a relative humidity of $50\% \pm 10\%$ for a minimum duration of 24 h. All room-temperature dry state fatigue tests were conducted on a universal testing machine with a capacity of ± 100 kN. Each specimen was carefully centered and securely gripped by the machine's hydraulic chucks. A tension–tension loading regime was applied, with fatigue tests performed under a constant-amplitude sinusoidal waveform. The “staircase method” was employed to determine the fatigue life threshold at 10^6 cycles using five pairs of stress levels. For the initial specimen, a load factor of 70% was recommended; subsequent load adjustments (increasing or decreasing) were determined based on the fatigue test results of the preceding specimen. The recommended stress level increment/decrement for each load step was 5% of the anticipated fatigue limit.

The specimen has been fabricated by hot-melt processing, which is the dominant solvent-free route for manufacturing high-performance carbon fiber-reinforced polymer (CFRP) prepreg, valued for its low void content and high batch-to-batch consistency. B-stage thermoset resin is first melted and slot-die coated onto release liners to form films with <1 μm thickness tolerance, while carbon fiber tows are spread into a uniform, gap-free web under ± 0.5 N closed-loop tension control to prevent fiber misalignment. The fiber web is sandwiched between two pre-coated resin films and fed through heated calender rolls held at 80–120 °C, a range tuned to the resin's minimum melt viscosity window to enable full infiltration of molten resin into filament interstices under low uniform pressure. The infiltrated prepreg is immediately quenched to halt crosslinking and lock the resin in a stable B-stage state, followed by in-line non-destructive quality verification, slitting, and winding. The T800 grade carbon fiber used in this article has a typical tensile strength of 5.6 GPa, which meets the definition of high-strength carbon fiber in ASTM D4018 [33].

As shown in Figure 1, type A and type C have the same width and thickness. The width is 15 mm, and the thickness is 1 mm. Type B has different size, whose width is 5 mm and thickness is 2 mm. The testing frequency was selected to ensure that the temperature of the specimens did not rise significantly. A thermocouple was affixed to the surface of each specimen to monitor its temperature and a heat dissipation device was employed,

ensuring that any increase in surface temperature did not exceed 10 °C throughout the test. Throughout the testing process, equipment status was continuously monitored, and any changes observed in the specimens were noted. Abnormal phenomena were recorded, along with the fatigue cycles to failure, the failure mode, and any other anomalies that occurred. Upon completion of the tests, the fracture surfaces of the failed specimens were preserved for subsequent fractographic analysis. In this study, the load waveform for the fatigue test utilized a sine wave, with a dynamic-to-static load ratio of 0.9 (corresponding to a stress ratio of 0.0526) and a loading frequency of 10 Hz.

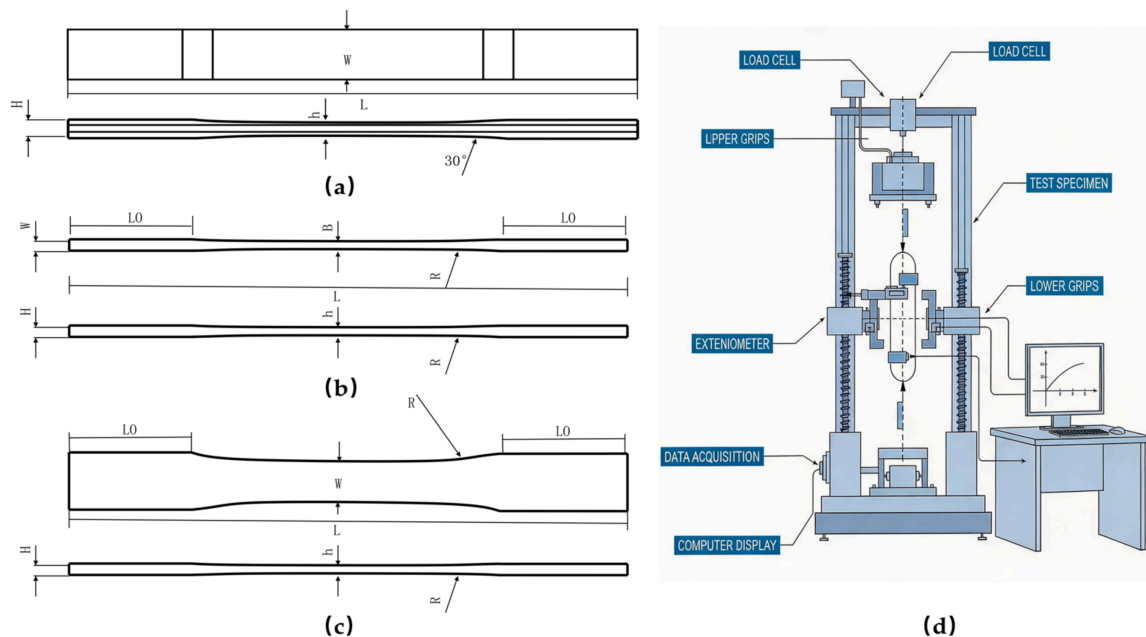


Figure 1. Diagram of test configuration. (a) A-type specimen; (b) B-type specimen; (c) C-type specimen; (d) schematic diagram of testing machine.

3. Results

3.1. Quasi-Static Test Results

First, as shown in Table 1, the ultimate strength of the unidirectional composite laminates was determined under quasi-static tension to provide a reference for fatigue loads in our subsequent tension–tension fatigue tests. Given the significant variations in the mechanical properties of composite materials, six specimens were selected for quasi-static tensile tests to enhance measurement accuracy, numbered sequentially from 001 to 006. In accordance with the test standard requirements, the width and thickness of each specimen were individually measured prior to testing. Longitudinal and transverse strain gauges were bonded along the midline on the surface of each quasi-static tensile specimen for their respective measurements. The test was conducted at a loading rate of 0.5 mm/min. Subsequently, the elastic modulus and ultimate strength of the unidirectional laminates were calculated using the corresponding theoretical equations.

Table 1. Quasi-static tensile test results.

Specimen Number	Width (mm)	Thickness (mm)	Load (KN)	Strength (MPa)	Mean Strength (MPa)	Strength Dispersion Coefficient (%)	Modulus (GPa)	Mean Modulus (GPa)	Modulus Dispersion Coefficient (%)
1	15.03	2.045	82.74	2692	2632	5.78	162	165	5.97
2	15.02	2.101	84.64	2682			164		

Table 1. *Cont.*

Specimen Number	Width (mm)	Thickness (mm)	Load (KN)	Strength (MPa)	Mean Strength (MPa)	Strength Dispersion Coefficient (%)	Modulus (GPa)	Mean Modulus (GPa)	Modulus Dispersion Coefficient (%)
3	15.08	2.089	85.21	2705	2632	5.78	179	165	5.97
4	14.99	2.096	78.86	2510			155		
5	14.98	2.054	79.11	2571			164		
6	15.01	2.032	80.28	2632			165		

3.2. Tensile Fatigue Test Results

The average maximum load obtained from our quasi-static tensile tests on unidirectional laminates was 167.47 KN, which was designated as the ultimate load for the subsequent tension–tension fatigue tests. Polymer matrix composites (PMCs) may retain structural integrity even under cyclic loading conditions where notable fatigue damage has accumulated. In the tests described below, the number of cycles at which specimen fracture occurred was recorded as the fatigue life corresponding to the applied load level. Three distinct fatigue load levels were defined: 80%, 75%, and 70% of the pre-determined ultimate load. The tension–tension fatigue tests were conducted with a stress ratio of 0.056 and a loading frequency of 10 Hz. Given the considerable inherent variability in fatigue test data, a total of six specimens were utilized for the fatigue tests. The dimensions and test results for the A- and B-type specimens are presented in the following tables.

As shown in the Tables 2 and 3, Configuration A specimens exhibited a higher critical stress level in the tensile fatigue tests compared to their Configuration B counterparts. Specifically, Configuration A specimens were able to last for 10^6 cycles at a load level two grades higher than Configuration B, meeting the test criteria for determining a material's tensile fatigue threshold. Accordingly, these results demonstrate that for specimens fabricated from the same material and tested under identical applied stress levels, Configuration A more accurately reflects the intrinsic tensile fatigue properties of the material. Furthermore, we posit that the width-to-thickness ratio of the specimen exerts a non-negligible effect on the accurate characterization of the material's intrinsic tensile fatigue performance; a systematic investigation was subsequently conducted to explore the size effect of the width-to-thickness ratio on fatigue performance.

Table 2. Tensile fatigue test results (A-type specimens).

Specimen Number	Width (mm)	Thickness (mm)	Load (KN)	Strength (MPa)	Maximum Dynamic Stress (MPa)	Fatigue Life (N)	Fatigue Life Logarithm (lgN)
1	14.93	1.073	80.93	2130	1009	3480	3.5
2	14.91	1.075	76.88	2023.5	959	506,731	5.1
3	14.92	1.075	76.88	2023.5	959	60,802	4.8
4	14.92	1.074	72.83	1917	908	1,000,000	6.0
5	14.91	1.076	72.83	1917	908	514,776	5.7
6	14.92	1.088	68.79	1810.5	858	1,000,000	6.0

Table 3. Tensile fatigue test results (B-type specimens).

Specimen Number	Width (mm)	Thickness (mm)	Load (KN)	Strength (MPa)	Maximum Dynamic Stress (MPa)	Fatigue Life (N)	Fatigue Life Logarithm (lgN)
1	5.01	2.108	22.50	2130	1009	64,388	4.8
2	5.01	2.102	21.31	2023.5	959	180,627	5.3

Table 3. Cont.

Specimen Number	Width (mm)	Thickness (mm)	Load (KN)	Strength (MPa)	Maximum Dynamic Stress (MPa)	Fatigue Life (N)	Fatigue Life Logarithm (lgN)
3	5.02	2.105	20.26	1917	908	325,394	5.5
4	5.02	2.104	19.12	1810.5	858	1,000,000	6.0
5	5.02	2.101	19.10	1810.5	858	827,072	5.9
6	5.03	2.109	19.21	1810.5	858	693,950	5.8

The failure mechanisms of quasi-static tension and fatigue are inherently distinct. During the tension–tension fatigue tests, thermocouples were employed to monitor the temperature of the gauge section on the specimen surface. Unlike in our quasi-static tension tests, the surface temperature rapidly increased from 28 °C to 37 °C after approximately 3000 fatigue cycles, remaining stable at around 38 °C for an extended duration. Prior to fatigue failure, a slight elevation in surface temperature was detected, followed by a sharp surge accompanying specimen fracture in which the peak temperature reached 97 °C. These findings demonstrate the utility of monitoring variations in temperature to predict impending fatigue failure; a slight rise in composite temperature can be used as an indicator of the exhaustion of their fatigue life.

As summarized in Tables 4 and 5, and Figure 2. Configuration C specimens demonstrated the ability to enable reliable, repeatable characterization of the material’s tensile fatigue properties across all evaluated environmental conditions. Accordingly, for future studies focused on characterizing the tensile fatigue performance of this class of materials, this configuration is recommended in order to obtain robust, high-quality test data.

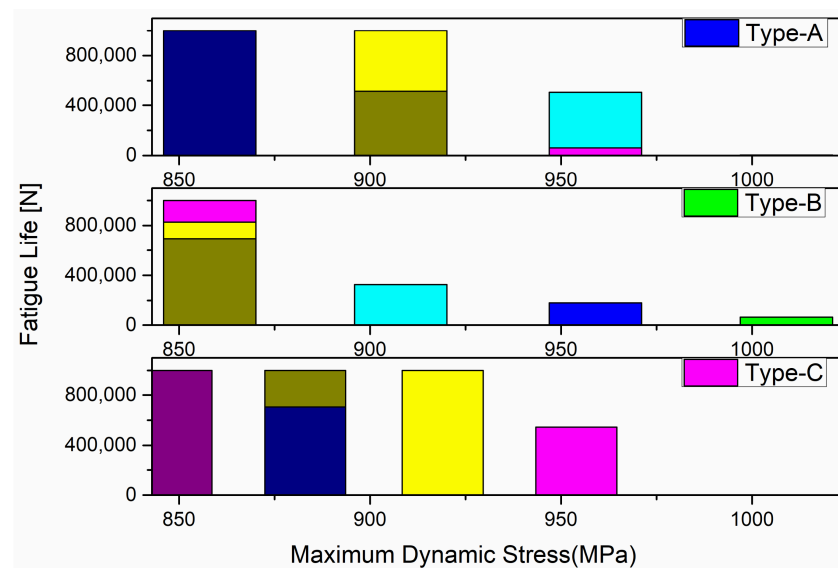


Figure 2. Results compared with different three types.

Table 4. Tensile fatigue results for C-type specimens.

Specimen Number	Strength (MPa)	Maximum Dynamic Stress (MPa)	Fatigue Life (N)
1	2015	954	544,590
2	1940	919	1,000,000
3	1865	883	1,000,000
4	1865	883	706,720
5	1790	848	1,000,000

Table 5. Tensile fatigue results for C-type specimens under ETW (55 °C, 75%) conditions.

Specimen Number	Strength (MPa)	Maximum Dynamic Stress (MPa)	Fatigue Life (N)
1	2015	954	131,346
2	2015	954	422,779
3	1940	919	1,000,000
4	1940	919	756,886
5	1940	919	180,081

4. Discussion

As shown in post-failure macroscopic observations, specimens of Configuration A suffered severe adhesive debonding and delamination at the interface between the reinforcing grip tabs and the specimen substrate during tension–tension fatigue testing. Failure initiated and propagated entirely within the grip-region reinforcing tabs rather than the specimen gauge section, meaning the resulting fatigue life data were non-representative of the material’s intrinsic performance. Specimens of Configuration B, which features a thickened grip region to mitigate tab debonding, exhibited longitudinal splitting within the grip area, with failure occurring via massive tow bundle fracture at the root of the grip-to-gauge transition region rather than crack initiation and growth in the gauge section. To eliminate these premature grip-region failure modes, post-failure analysis was also performed on a third, optimized specimen configuration. Post-test inspections confirmed that this optimized design consistently produced fracture initiation and full propagation within the gauge section, with no sub-critical premature damage or incipient failure observed in the grip or transition regions prior to final fracture. This result confirms that the optimized configuration enables robust, accurate characterization of the material’s intrinsic tension–tension fatigue performance.

As shown in Figure 3, the failure mechanism of carbon fiber-reinforced polymer (CFRP) laminates is inherently stochastic. According to the weakest link theory, structural failure begins at randomly distributed microscopic defects, such as voids, fiber breakages, or resin-rich areas. Consequently, as the volume of the component increases, the probability of encountering a critical defect rises significantly, leading to a degradation in apparent strength. To quantify this geometric influence on fatigue performance, we incorporated a two-parameter Weibull distribution model. Assuming the shape parameter m remains constant for a specific material system, the characteristic strengths of components with different effective volumes can be calculated using the following power law scaling equation:

$$X(V) = X_0 \cdot \left(\frac{V_0}{V} \right)^{1/m} \quad (1)$$

where X_0 and V_0 denote the characteristic strength and effective volume of the baseline specimen (e.g., standard coupon), respectively; $X(V)$ represents the corrected strength for the target component with volume V ; and m is the Weibull modulus, which characterizes the dispersion of material strength. In this study, the Weibull modulus was determined to be 26 based on our static tensile tests which varied specimen volume, indicating that static strength serves as a geometry-dependent variable rather than a fixed material constant.

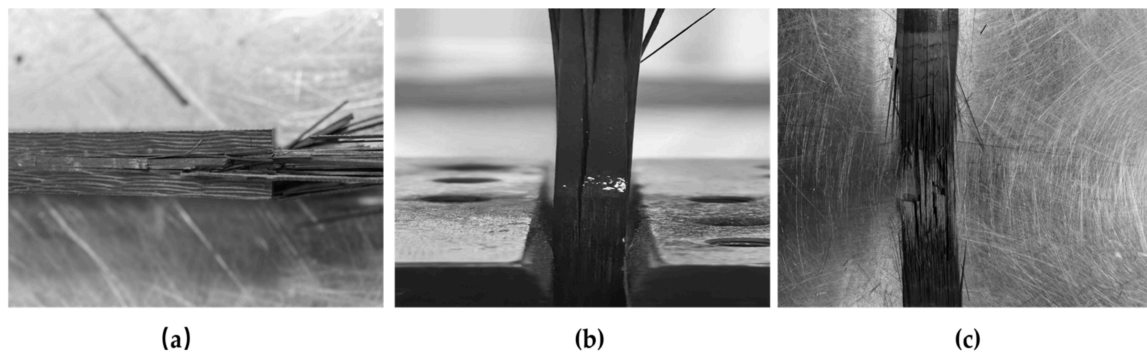


Figure 3. Three types of failure mode. (a) A-type; (b) B-type; (c) C-type.

The Gathercole model is widely adopted for its efficiency in capturing the anisotropic and asymmetric tension–compression fatigue envelopes of composites. However, conventional applications often neglect the impact of size effect on stress normalization factors. To enhance the fidelity of fatigue life prediction for large-scale structures, we propose a sequential coupling framework. First, the baseline static tensile (X_T) and compressive (X_C) strengths are updated to the size-dependent parameters $X_T(V)$ and $X_C(V)$, using Equation (1) based on the target geometry (L, W, T). Subsequently, these modified strength parameters are integrated into the normalization process of the Gathercole model.

The modified equivalent stress parameter, u , is formulated as

$$u = \frac{\ln(a_V/f)}{\ln[(1-q_V)(c_V+q_V)]} \quad (2)$$

Here, the normalized stress amplitude (a_V), normalized mean stress (q_V), and compression-to-tension ratio (c_V) are redefined as functions of the effective volume as follows:

$$a_V = \frac{\sigma_a}{X_T(V)}, q_V = \frac{\sigma_m}{X_T(V)}, c_V = \frac{X_C(V)}{X_T(V)} \quad (3)$$

By substituting the modified parameter u into the fatigue life equation, we obtain

$$u = A + B \lg N \quad (4)$$

The fatigue failure of carbon fiber-reinforced polymers (CFRPs) is a complex, progressive process of damage [36], involving matrix cracking, fiber breakage, and delamination. Of the existing life prediction methodologies, the Gathercole constant model is widely adopted for its efficacy in unifying fatigue data under various stress ratios (R) through a single control parameter, f . This model normalizes complex stress states into a damage parameter, u , establishing a linear correlation with the fatigue life logarithm ($\lg N$). However, the conventional application of the Gathercole model typically treats f as an intrinsic material constant, thereby neglecting the significant “size effect” often observed in composite materials. According to Weibull’s statistical strength theory and investigations into free-edge effects, the fatigue performance of laminates exhibits a pronounced dependence on specimen volume or surface area. In the experimental phase of this study, a distinct geometric disparity was noted between the tension–tension ($R = 0.1$) and compression–compression ($R = 10$) fatigue specimens, characterized by average width-to-thickness ratios (W/T) of approximately 14.3 and 9.6, respectively. Neglecting this geometric constraint and employing the global constant f resulted in a divergence of prediction accuracy across different stress states, failing to capture the fatigue life evolution induced by specimen geometry. To address this limitation, we propose a modified Gathercole model incorporating a geometric correction factor. The width-to-thickness ratio ($\lambda = W/T$) was selected as

the governing geometric parameter to characterize the influence of specimen dimensions on fatigue damage accumulation. In this modified framework, the constant parameter assumption is relaxed, and f is redefined as a function of geometry, $f(\lambda)$. Assuming that the impact of the size effect follows a power law distribution, the correction function is expressed as

$$f(\lambda) = f_{ref} \cdot (\lambda/\lambda_{ref})^k \quad (5)$$

where f_{ref} represents the baseline model parameter at the reference ratio λ_{ref} (taken here as the tension specimen geometry) and k denotes the size sensitivity index. This formulation allows non-linear shifts in the constant life curve, caused by variations in the cross-sectional aspect ratio, to be described quantitatively. When $k \neq 0$, the model explicitly accounts for the size-induced variability in fatigue resistance, providing a more rigorous phenomenological description than the classical model. A global optimization strategy based on the goodness of fit was implemented to identify the optimal model parameters. The objective was to maximize the linearity of the experimental data in the transformed $u - \lg N$ coordinate system across all loading conditions. An objective function, defined by the coefficient of determination (R^2) of the linear regression, was established for the aggregate dataset comprising both the tension and compression fatigue results, while a non-linear optimization algorithm was employed to iteratively search the parameter space (f_{ref}, k) , thereby automatically determining the correction factors that minimize data dispersion. This numerical optimization yielded a non-zero value for the sensitivity index k , confirming that the fatigue life of the T800 carbon fiber unidirectional plate is significantly influenced by the specimen's cross-sectional geometry.

From the perspective of physical mechanisms, the variation in the width-to-thickness ratio alters the proportion of the free-edge region relative to the bulk cross-section. In unidirectional laminates, the three-dimensional stress concentration at the free edges is the primary mechanism driving early-stage delamination. The modified model, as shown in Figure 4, through the dynamic adjustment of f , effectively compensates for the systematic errors introduced by the dimensional inconsistency between tensile and compressive specimens. Consequently, it demonstrates superior convergence, with data points under different stress ratios collapsing more tightly onto a single master curve. This enhancement significantly improves the reliability of S-N curve predictions over the full range of stress ratios, providing a robust theoretical basis and a precise engineering tool for assessing the fatigue life of composite structures with complex geometric features. In this regard, predictions were performed using the constant life model proposed by Gathercole et al. [37]. To account for the geometric influence, the static strength parameters were modified based on Weibull's weakest link theory [38], as discussed at length by Wisnom [39] for application to unidirectional composites. The specific model parameters for T800 carbon fiber, including the modified shape factor f , were adopted from the experimental work of Zhang [40].

During tensile fatigue testing performed under high-temperature dry and wet ambient conditions, Configuration A specimens suffered from tab (reinforcing grip patch) debonding, which rendered the corresponding test data unusable. This failure was attributed to severe degradation of the adhesive bonding the tabs to the specimen grip sections due to the combined effects of high temperature and dry/moist exposure, precluding accurate characterization of the material's intrinsic tensile fatigue properties. Building on our prior investigation into the size effect of the width-to-thickness ratio on fatigue performance, we developed a novel integrally machined specimen configuration, designated as Configuration C. For this design, the gauge section width was kept identical to that of Configurations A and B to ensure consistent loading conditions, while the grip sections were widened and thickened to eliminate the need for bonded reinforcing tabs.

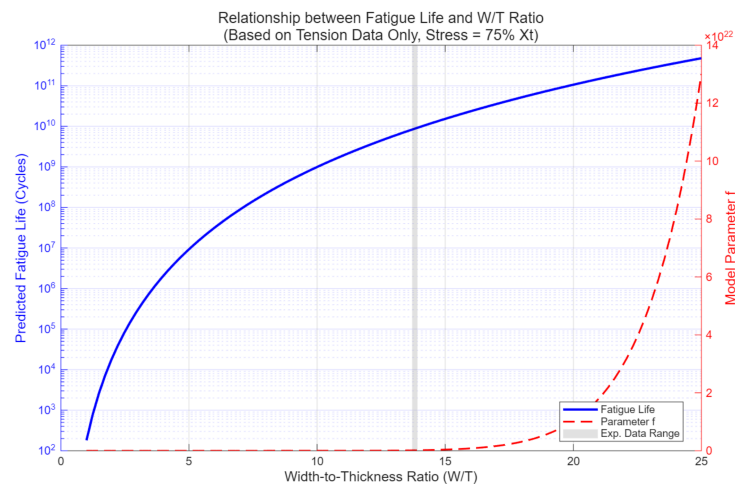


Figure 4. Relationship between fatigue life and W/T ratio.

5. Conclusions

This study systematically investigated the tensile fatigue performance of T800-grade CFRP unidirectional laminates using two widely adopted fatigue tensile test specimen configurations. Our test results confirm that the width-to-thickness (w/t) ratio of the specimen gauge section acts as a critical size effect factor dominating the measured tensile fatigue performance of such laminates.

Within the parameter range of standard specimen configurations specified for aerospace composite testing, specimens with low w/t ratios are prone to generate additional interlaminar stresses at the gauge section edges, which induce extrinsic edge delamination prior to the intrinsic fatigue failure of the material, leading to significantly underestimated fatigue life and high data scatter. In contrast, straight-sided specimens with larger w/t ratios effectively suppress such edge-initiated non-intrinsic failure, yielding fatigue data with lower scatter and higher fidelity to the actual intrinsic fatigue life of the composite.

However, conventional straight-sided specimens rely on adhesively bonded reinforced tabs for gripping, which frequently suffer from premature adhesive failure at the tab-laminate interface when tested under hot/wet conditions or high-temperature environments (especially when the test temperature exceeds the glass transition temperature, T_g , of the adhesive). Such premature interface failure renders the entire test invalid, and has long been a common technical bottleneck for fatigue characterization of composites under extreme service conditions. To address this challenge, we propose a novel straight-sided tensile fatigue specimen configuration with co-cured widened gripping ends. Unlike conventional tabbed specimens, this design replaces the extra adhesively bonded tabs with a widened gripping section that is co-cured integrally with the laminate gauge section, fundamentally eliminating the risk of adhesive interface failure. Verification tests demonstrate that this new configuration exhibits no gripping end failure under extreme conditions including 70 °C hot/wet exposure testing, confirming its capability to accurately characterize the intrinsic fatigue performance of composites under extreme environments.

The findings of this work not only clarify the governing rule of key size effects on tensile fatigue testing of unidirectional CFRP laminates, providing quantitative guidance for parameter selection of standard fatigue specimens, but also offer a practical solution to the common technical bottleneck of composite fatigue testing under extreme environments. The proposed specimen configuration can serve as a valuable reference for future fatigue performance characterization of advanced composites and revision of relevant test standards.

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Abbreviations

The following abbreviations are used in this manuscript:

CFRP	carbon fiber-reinforced polymer
PMCS	polymer matrix composites

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