

EXPERIMENTAL STUDY ON THE FATIGUE PERFORMANCE OF CFRP BEAMS WITH STRUCTURED SURFACE LOAD INTRODUCTION UNDER CYCLIC LOADING

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ABSTRACT

CFRP is widely used in lightweight structures subjected to cyclic loading. However, the fatigue performance at the structural level, particularly with mechanical joints, remains insufficiently understood. This study investigates the fatigue behavior of quasi-isotropic CFRP square tubes under cyclic 3-point bending, with a focus on a load introduction concept using bolted connections with structured surface plates. The specimens are tested under fully reversed loading at 1 Hz. Quasi-static baseline tests reveal linear behavior up to failure and high reproducibility between specimens. Cyclic tests show a clear increase in fatigue life with decreasing load amplitude. Hysteresis analysis reveals asymmetric behavior and narrowing around the zero-crossing prior to failure, especially in high-cycle specimens. The specimen with the highest cycle count exhibited a distinct fiber fracture on the tensile side, suggesting a change in failure mode compared to quasi-static loading. The results highlight the relevance of the hysteresis loop shape as a potential indicator for fatigue damage and structural monitoring. The findings underscore that fatigue failure may occur in locations different from those under static loading, suggesting that conventional design approaches based on static safety factors may be insufficient for the design of CFRP structures.

1 INTRODUCTION

Carbon fiber reinforced polymers (CFRP) are increasingly used in lightweight structural applications due to their excellent strength-to-weight ratio, corrosion resistance, and stiffness. They are well established in high-performance industries such as aerospace, automotive, and wind energy [1]. With rising production volumes and falling costs, CFRP has also become economically viable for

simpler structural components, such as square tube profiles, where mechanical performance and cost-efficiency must be balanced [2]. These components are gaining relevance in applications that demand robustness under repeated mechanical loading.

Cyclic loads are common in many operational environments. Despite the damage-tolerant nature of CFRP laminates under fatigue loading, the long-term performance of composite structures remains difficult to predict – especially at the structural level [3]. Most studies are limited to small-scale coupon specimens or highly application-specific configurations, leaving a research gap between elementary material tests and full-scale system evaluations [4].

A critical factor for structural CFRP components is a reliable load introduction. Bolted connections are widely used due to their mechanical reliability and ease of disassembly. However, they locally interrupt the fiber alignment and induce matrix cracking or delamination, making the joint region particularly vulnerable to fatigue degradation. Previous research has shown that structured surfaces at the interface can improve the load transfer capabilities of bolted joints by enhancing both mechanical interlocking and friction [5]. Understanding the fatigue behavior of such connections under realistic loading is essential for ensuring structural reliability and safe design margins. Moreover, being able to detect or predict fatigue-induced degradation is highly relevant for the development of structural health monitoring systems. In particular, hysteresis loop evolution under cyclic loading offers a promising approach for characterizing internal damage states [6], [7].

This study aims to address the outlined gap by investigating the fatigue performance of quasi-isotropic CFRP square tube beams under cyclic 3-point bending. A special focus is placed on the role of bolted load introduction with structured surfaces. The work builds upon earlier investigations of small-scale joint behavior and evaluates the structural-level fatigue response, with attention to both global mechanical performance and fatigue-induced changes in hysteresis characteristics.

2 RESEARCH PROBLEM AND OBJECTIVE

Fatigue in CFRP laminates is generally considered damage-tolerant, with gradual degradation rather than sudden failure. However, the load introduction zone remains a critical weak point, where local stress concentrations can initiate damage and accelerate failure processes [8]. Current research on cyclically loaded CFRP connections is fragmented and often based on simplified coupon tests, which limits its applicability to structurally relevant components [4].

Bolted connections are widely used for load introduction in CFRP due to their mechanical robustness, disassembly capability, and suitability for high force transfer. The load is transmitted through bearing stress, directly from the bolt into the laminate. However, the required drilling of holes leads to fiber interruption, causing matrix cracking and delamination in the surrounding region, which compromises structural integrity [9]. The fatigue strength of such connections can be improved through interference fits [8] and clamping pressure, although these effects depend strongly on geometry and assembly parameters [9]. Failure mechanisms in bolted CFRP joints can be categorized into four main types, each influenced by geometry and boundary conditions [10]. Bearing failure is considered the most desirable mode. It occurs as a localized compression failure near the bolt, typically characterized by resin crushing and fiber buckling. This failure is less brittle and more damage-tolerant, and is favored when a high plate width-to-hole diameter ratio is maintained [11]. In contrast, net-tension failure is a brittle mode resulting from high tensile stresses across the remaining ligament between the hole and the edge. It typically occurs when large bolts are used in narrow components, leading to sudden transverse cracking and rapid failure. Shear-out failure is another brittle mechanism, characterized by shear fracture along the bolt axis, often occurring when the end distance is too small. It frequently appears as a secondary failure following bearing damage, particularly in in-plane loading scenarios [12]. Lastly, cleavage failure combines features of net-tension and shear-out. It initiates at the end of the plate, especially when both edge and end distances are insufficient and the longitudinal fiber content is high, leading to crack propagation along an inclined path. Ensuring proper geometric ratios helps to avoid this mode [13]. To mitigate these failure mechanisms, it is essential to maintain precise hole manufacturing and sufficient edge distances [14]. Additional measures, such as embedded metal foils or localized reinforcement layers, can improve bearing strength and reduce sensitivity to geometric constraints [15]. Despite these measures, fatigue failure in bolted CFRP

connections remains difficult to predict, as it is highly dependent on load spectra, joint design, and laminate configuration [16].

Previous research has primarily focused on idealized test coupons. To address the lack of structural-level data, the present study investigates the fatigue performance of quasi-isotropic CFRP square tubes under cyclic 3-point bending. The aim of this study is to provide experimental data on the fatigue behavior of CFRP components at the structural level and to evaluate the effectiveness of a load introduction concept based on bolted connections with structured surfaces. By applying cyclic bending loads to full-scale square tube specimens, this work seeks to identify dominant failure mechanisms and assess the stability of the connection under fatigue.

3 SPECIMEN DESIGN AND TESTING APPROACH

The fatigue behavior of CFRP structures is investigated using a 3-point bending test setup. The test specimens consist of CFRP square tubes with dimensions of $75 \times 75 \times 750$ mm and a wall thickness of 3 mm. The geometric dimensions of the specimens are shown in Figure 1, including mean values across all beams and their maximum deviations. Dimensions up to 75 mm were measured using a micrometer, while larger values were obtained with a caliper. The corner radius was determined via optical microscopy. Notable deviations are observed in the wall thickness and corner radius, whereas all other dimensions exhibited high dimensional accuracy. For the milled bolt holes, the measured radius deviation is at the limit of the measurement accuracy.

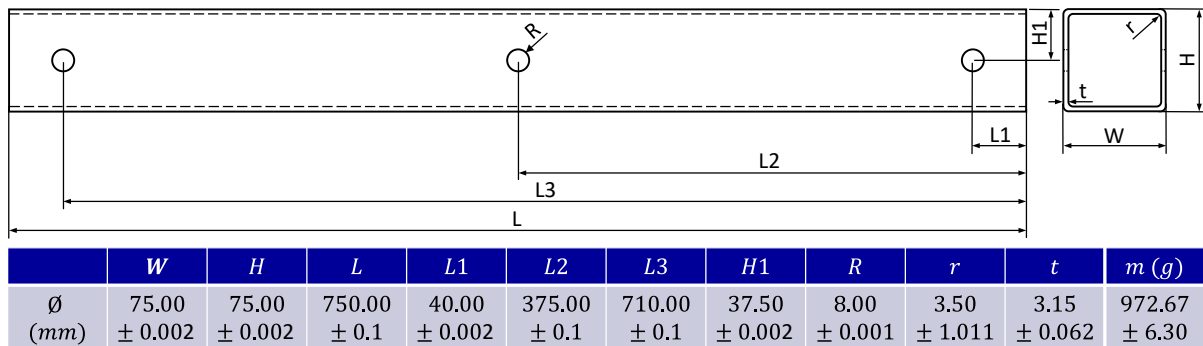


Figure 1: Dimensions of the test specimens.

The laminate was manufactured using a prepreg process in an aluminum negative mold and featured a 12 layer quasi-isotropic layup, following the stacking sequence $[0^\circ, 60^\circ, -60^\circ, 0^\circ, -60^\circ, 60^\circ]_s$. To introduce the load, a bolted connection with structured surface plates is developed (see Figure 2). The bearing plates with structured contact surfaces are mounted on threaded pieces, which are pressed against the CFRP square profile by a locknut. These threaded elements are then fitted onto bolts through which the load is applied. This design enables both form-fit and clamping effects, aiming to enhance load transfer by increasing contact friction and minimizing stress concentrations. The structured surfaces featured pyramidal elements with a tooth height of 0.3 mm. The tooth geometry was selected based on literature [17] to ensure high friction and allowable surface pressure. The holes in the CFRP profile are manufactured with high dimensional accuracy to ensure a precise fit between bolt and laminate, as literature shows that even small clearance gaps can lead to a significant reduction in load transfer capacity [14].

To prevent overheating during high-cycle testing, compressed air is introduced through the hollow interior of the CFRP beam to provide active cooling. On the opposite side of the profile, an FFP2 filter is installed. This serves a dual purpose: first, to collect fine dust particles that might be expelled by the cooling airflow; and second, to create flow resistance, thereby improving air distribution through the beam and enhancing the overall cooling efficiency.

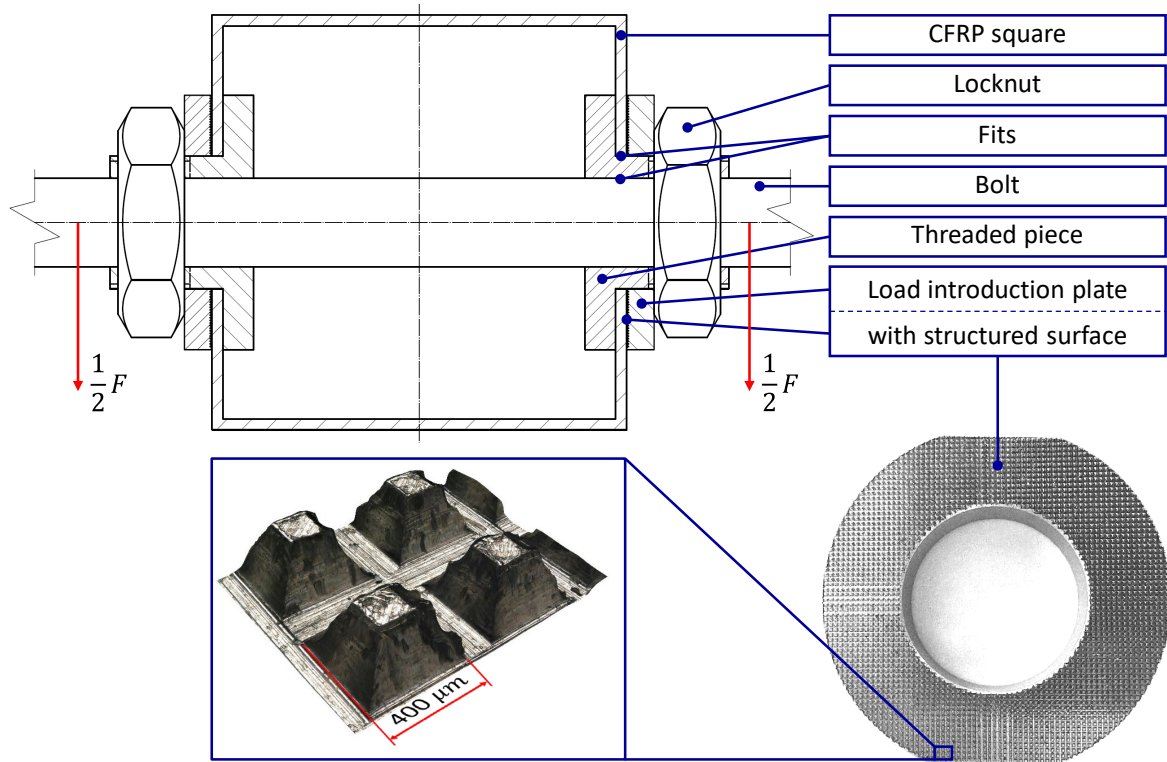


Figure 2: Load introduction design with structured surface and three-dimensional enlargement of the pyramid-shaped surface structure.

The experiments were carried out on a servo-hydraulic testing system with a maximum actuator force of 125 kN. The two outer supports are equipped with roller-bearing guides to compensate for axial displacement caused by beam deflection. Load is measured via a 125 kN load cell, and displacement is recorded both by the integrated actuator position sensor and an external laser displacement sensor, which is aligned with the midplane of the test setup. In addition, the temperature at the top flange of the CFRP profile is monitored using a Type K thermocouple.

At the beginning of the test series, two quasi-static destruction tests were performed to determine the maximum load capacity of the CFRP beams. This value serves as the basis for selecting the amplitude for the subsequent fatigue tests. The following cyclic tests were conducted under fully reversed loading at a frequency of 1 Hz. The first fatigue test was carried out at 85% of the previously determined maximum load, while the load amplitude was gradually reduced in the subsequent tests to assess the fatigue performance at lower stress levels.

4 RESULTS AND DISCUSSION

The structured surface embedding using the pyramidal profile was successfully implemented. No loosening of the locknuts was observed during cyclic testing, indicating stable mechanical fixation throughout the test duration. The cooling system proved effective, with a maximum temperature increase of only 1 °C at the measurement point. In contrast, a reference test without internal cooling, conducted at 1 Hz and a cyclic load of 45 kN, resulted in a temperature rise of approximately 23 °C after 30 minutes.

4.1 Quasi-static testing

The quasi-static tests reveal a linear force–displacement behavior up to the point of failure, indicating elastic material response across the tested load range. Maximum load capacity is observed at approximately 53 kN. Figure 3 shows the force–displacement diagram obtained from the quasi-static bending tests. Failure occurs suddenly, suggesting a brittle failure mechanism under bending load. A very good agreement is observed in the linear-elastic range of the force–displacement response.

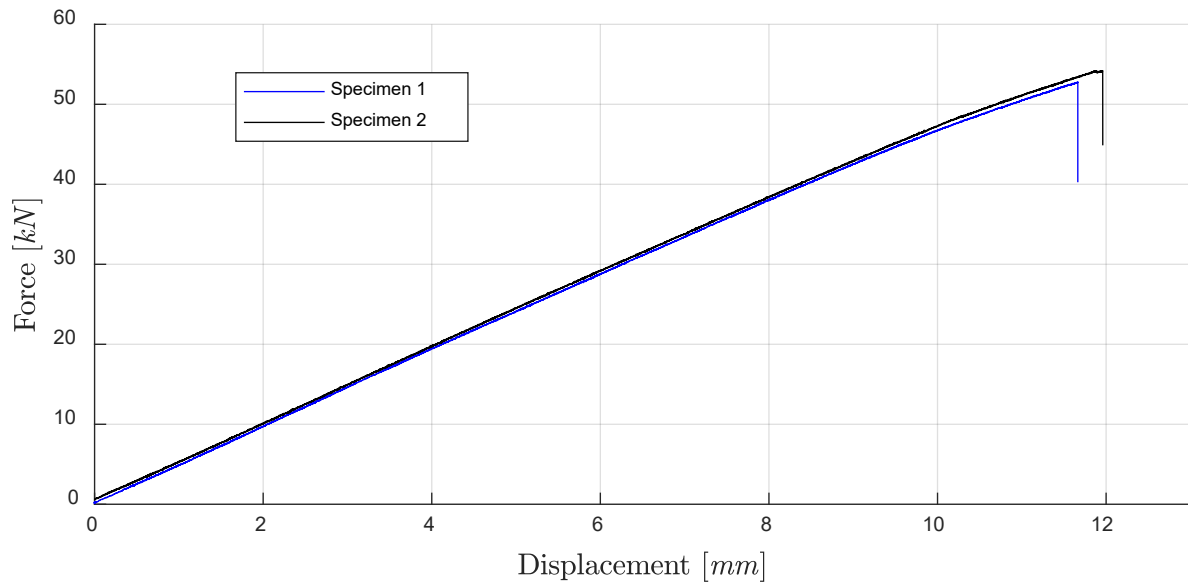


Figure 3: Force-displacement diagram of quasi-static tests.

Figure 4 presents the failure patterns of the two quasi-static specimens. The beams exhibit local buckling at the lower flange, combined with matrix detachment and interlaminar delamination, consistent with typical compression-induced failure mechanisms in fiber-reinforced polymer structures under bending. These failures are driven by local instability in matrix-dominated regions, which are especially sensitive to interlaminar shear stresses and separation. Notably, Specimen 1 failed at an off-center position, rather than directly at midspan where the highest bending moment occurs, and thus the failure, would be expected. A possible explanation for this behavior is that the load introduction locally reinforces the beam, especially the vertical webs of the square tube, thereby stabilizing the midsection and shifting the critical failure zone outward.

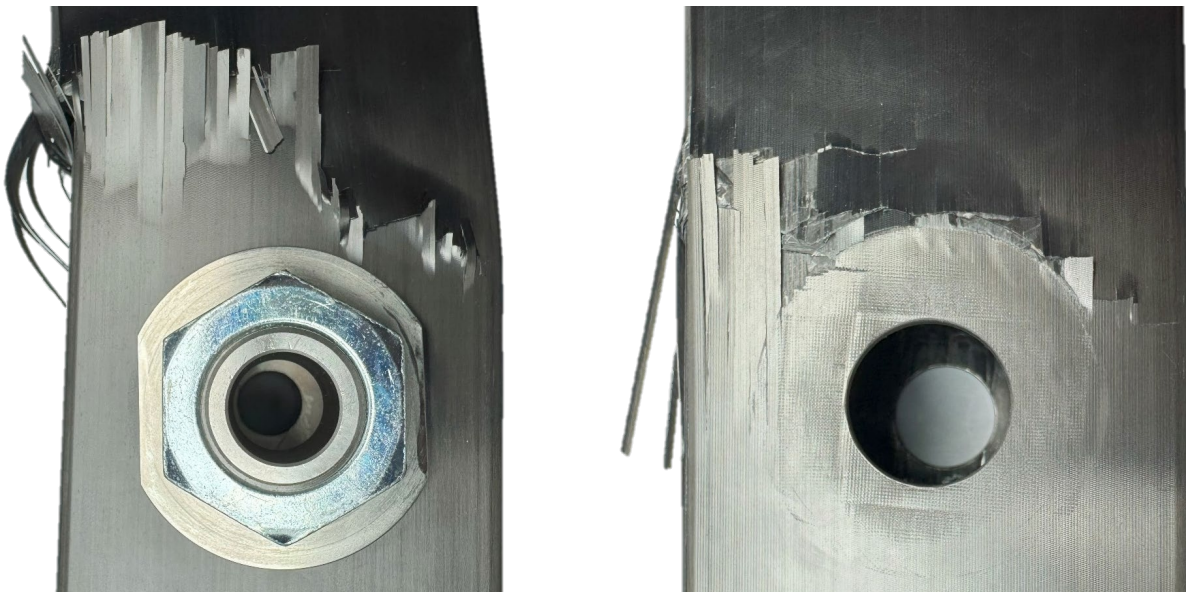


Figure 4: Failure of Specimen 1 with load introduction (left) and Specimen 2 without load introduction (right).

Specimen 2 exhibited a central failure fracture, as shown in Figure 4 (right). The fracture path runs around the load introduction region. As with Specimen 1, this suggests a stabilizing effect of the load introduction unit, likely due to the local reinforcement.

4.2 Cyclic testing

To evaluate the fatigue performance of the CFRP beams under cyclic loading conditions, a series of 3-point bending tests was carried out at decreasing load amplitudes. Table 1 summarizes the applied maximum force and the corresponding number of cycles to failure for each specimen. As expected, the number of cycles to failure increases with decreasing load level, indicating a typical fatigue response. While specimens tested at higher loads failed within a few thousand cycles, Specimen 7, sustained nearly 150,000 cycles before failure. The comparatively low cycle count of Specimen 5 suggests a potential outlier.

Test Specimen	Force [kN]	Number of Cycles to Failure
Specimen 3	45	2077
Specimen 4	43	10312
Specimen 5	40	2681
Specimen 6	38	12977
Specimen 7	35	149480

Table 1: Overview of tests.

Figure 5 compares the hysteresis behavior of Specimen 7 at cycle 100 and cycle 149,479, the cycle before final failure. A reduction in hysteresis area is observed at the later stage, indicating decreased energy dissipation, which is characteristic of advanced material degradation [18]. The loading and unloading paths converge near the zero-crossing, suggesting a nearly elastic response with no measurable plasticity or damping, a sign of structural exhaustion. While the overall stiffness appears unchanged, internal damage accumulation is likely near critical. A slight asymmetry and narrowing of the curve further points to localized effects such as delamination, matrix cracking, or fiber-matrix debonding. This observation is consistent with findings, where individual fiber bundles delaminated at the sides or corners of the beam, away from the eventual failure location, prior to global failure. This indicates that localized damage initiation can occur independently of the final fracture zone and further supports the interpretation of progressive internal degradation despite externally stable load-displacement behavior.

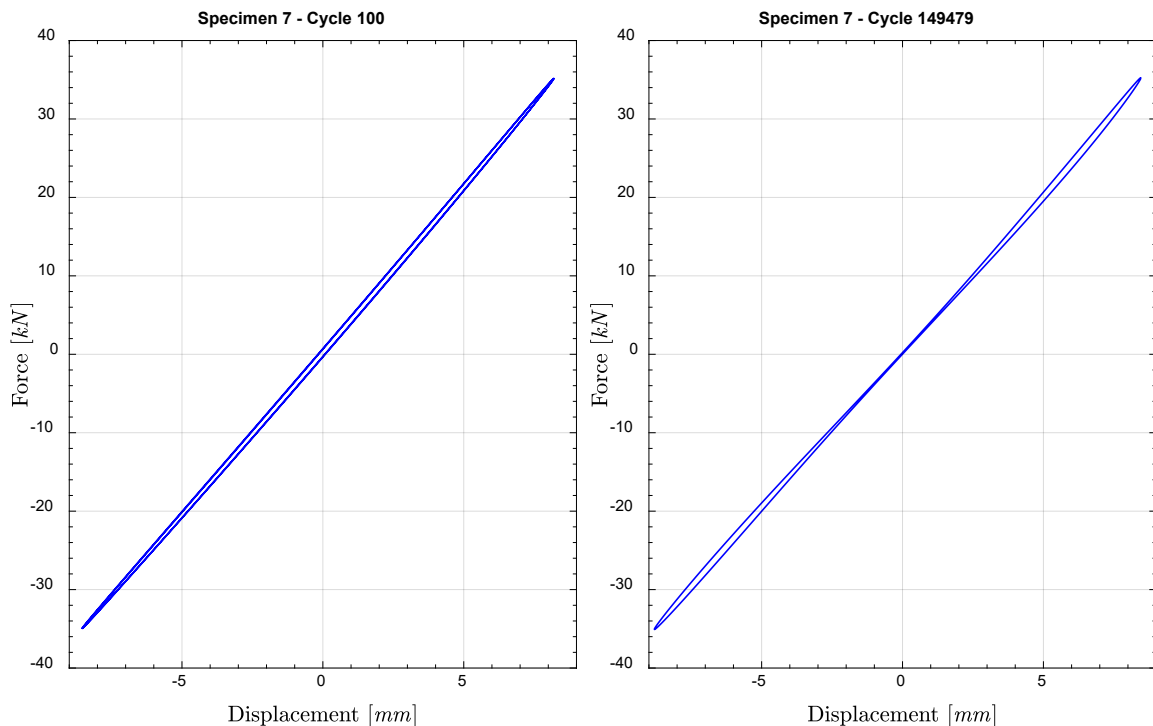


Figure 5: Hysteresis behavior of Specimen 7 at cycle 100 and 149479.

These features collectively indicate that the material has exhausted its damage tolerance and that failure is imminent. This progression highlights how the collapse of the hysteresis loop at the neutral axis could be precursor of final failure in fatigue-loaded composites. Such behavior could be relevant for structural health monitoring, as it highlights the need to detect early-stage internal damage. Localized delamination or fiber–matrix debonding could serve as early indicators of fatigue degradation. This aspect will be investigated in future tests. To enable a more detailed analysis of local damage progression, strain gauges will be applied at critical locations on the beam surface. This will allow for a broader and more spatially resolved dataset.

The convergence of the loading and unloading paths near the zero-crossing in Specimen 7 developed progressively over the final 40,000 cycles. A similar trend is observable in Specimens 4 and 6, where the hysteresis loops also narrow around the neutral axis as failure approaches. Furthermore, all specimens exhibit increasing asymmetry in their hysteresis behavior toward the end of their fatigue life, though with varying degrees of intensity.

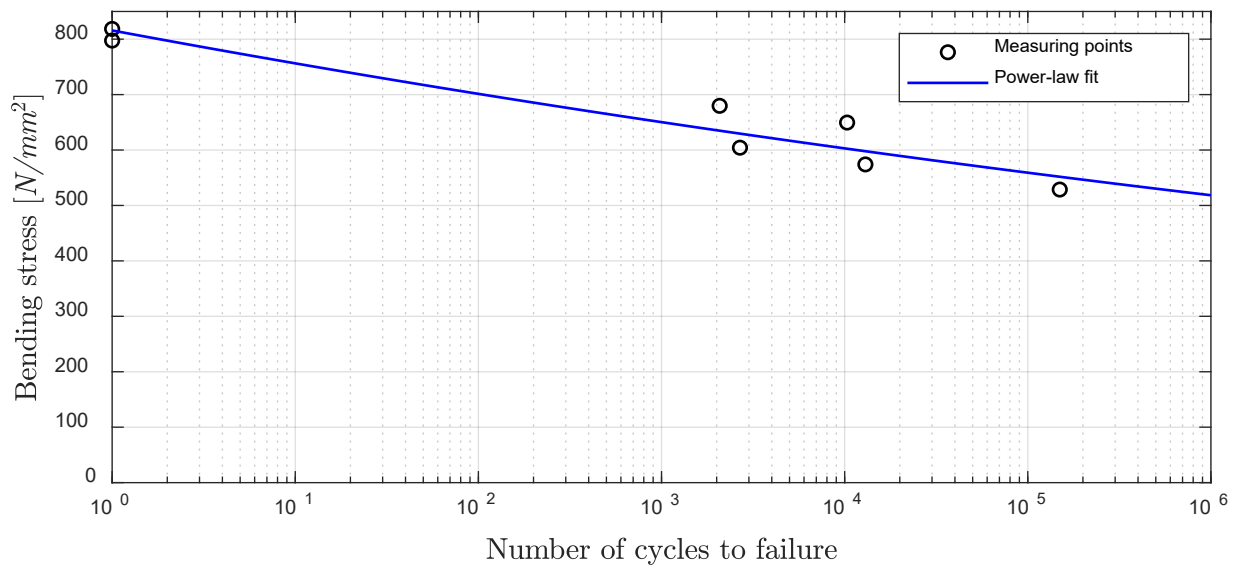


Figure 6: S-N curve with power-law fit trendline.

Figure 6 displays the bending stress versus the number of cycles to failure for all tested specimens. The results from the quasi-static tests are included as reference points with a cycle count of 1. To illustrate the overall trend in fatigue behavior, a power-law fit is applied to the data. This trendline provides a first approximation of the fatigue life curve, highlighting the expected decrease in maximum stress with increasing cycle number.

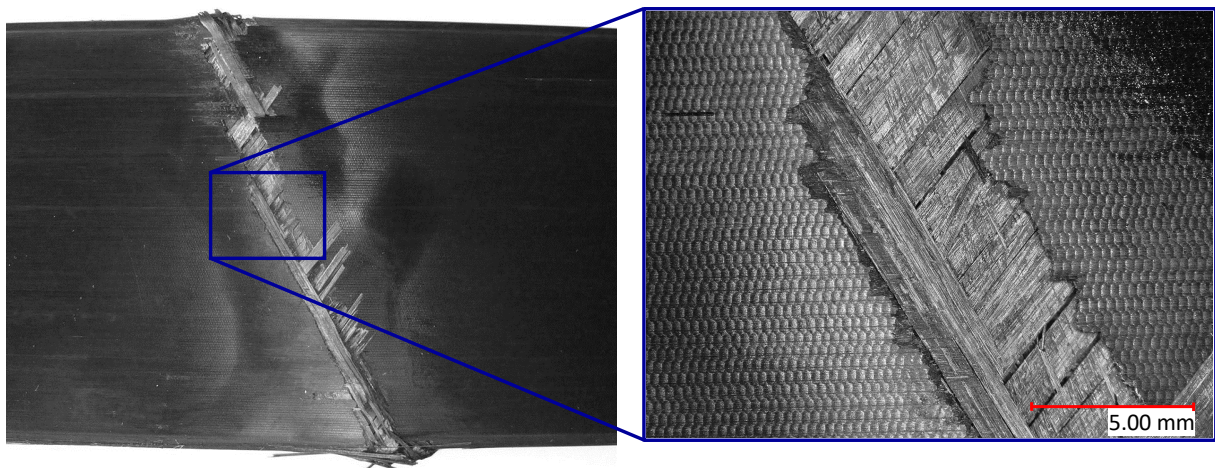


Figure 7: Failure of Specimen 7 with magnified view.

At low cycle counts, the observed failure modes are similar to those in the quasi-static tests, characterized by local buckling and delamination at the lower flange. However, at cycle numbers exceeding 10^4 , delamination occurs on both sides of the specimen, which is consistent with the alternating loading applied during fatigue testing.

An exception appears in Specimen 7, where a distinct failure mode emerges. Instead of buckling on the compression side, as typically seen, the failure occurred on the tension side of the profile, where a fiber fracture accrued. This result is shown in Figure 7. Such a shift in failure location under fatigue loading is particularly relevant for design practice, as it challenges the assumption that fatigue failure occurs at the same critical location as static failure. In many current design approaches, fatigue is accounted for by applying a global safety factor to the static strength. This strategy may be insufficient when fatigue failure initiates in different regions of the structure. Since only a single specimen was tested in this high-cycle regime, further tests are planned to statistically validate this observation and assess its reproducibility.

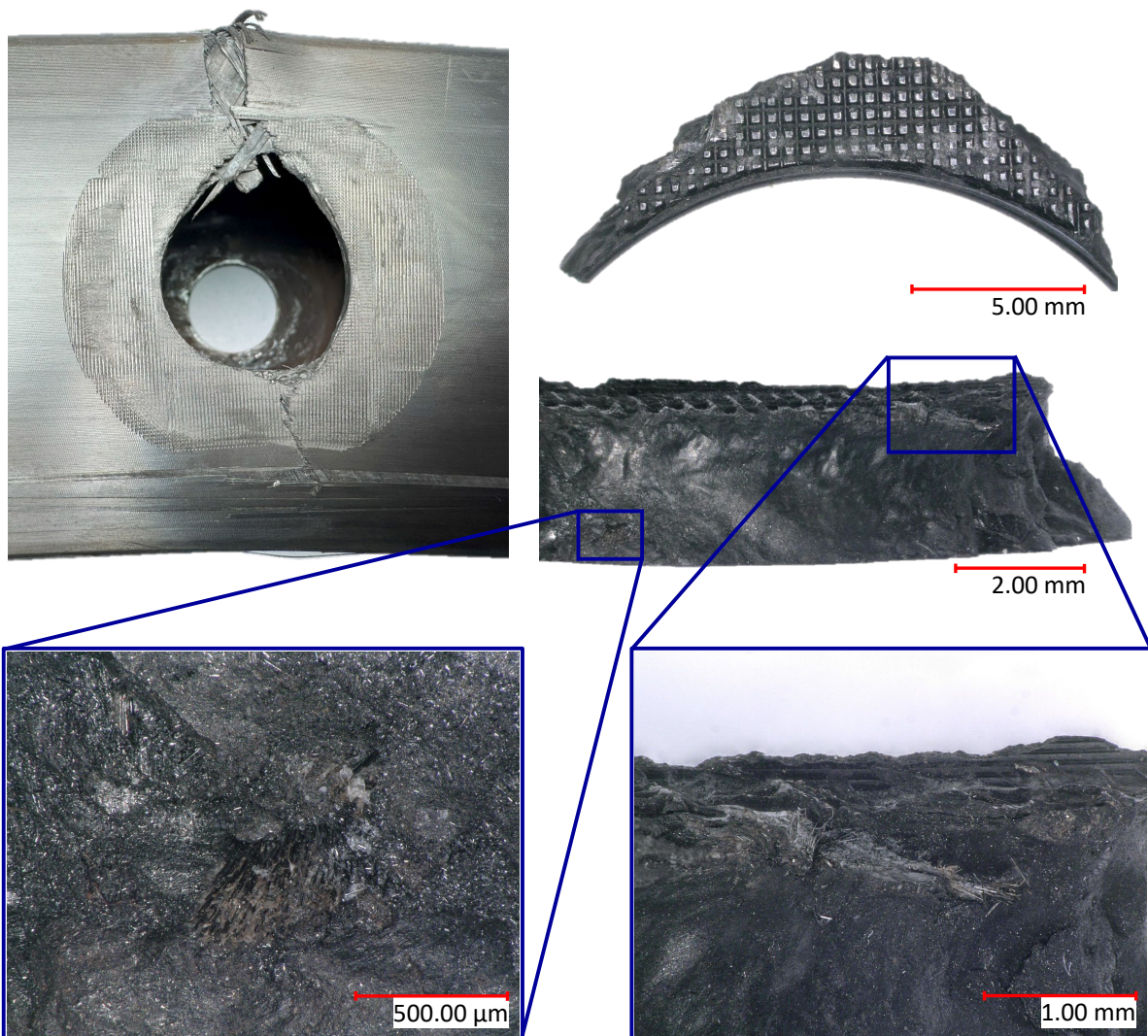


Figure 8: Top view of the damage on Specimen 7 (top left) and the detached fragment (top right). The fracture surface is shown in the middle right image, with magnified views of the fracture edge and exposed fiber bundles (bottom).

None of the tested specimens exhibited catastrophic failure at the load introduction area. However, in two cyclically tested specimens, seizure (galling) occurred between the bolt and the threaded insert. In both cases, localized damage to the CFRP in the load introduction zone is observed (see Figure 8).

The material appears brittle, and during disassembly, a portion of the laminate fractured and detached, shown on the right top in Figure 8. Below that, the fracture surface of the detached laminate fragment is shown. The surface exhibits a dark, discolored appearance, which visually resembles thermal damage or burning. Only two small areas with visible fibers can be identified, which are shown in magnified view in the lower part of the figure.

A possible explanation is that localized frictional heating during galling led to temperatures exceeding the glass transition temperature of the CFRP matrix, resulting in material degradation. Although this was not the primary failure mode of the beams, the finding emphasizes the critical importance of the load introduction zone in the fatigue design of CFRP structures. Even if structural failure occurs elsewhere, thermo-mechanical interactions at the interface may compromise long-term performance and must be accounted for in design and monitoring strategies.

5 CONCLUSION

This study contributes to the understanding of the fatigue performance of CFRP structures at the component level. CFRP square beams were tested under both quasi-static and cyclic 3-point bending, with the load introduced via structured bolted plates that ensured both form-fit and force-fit conditions. The quasi-static tests showed good repeatability across specimens, with linear behavior up to failure, followed by sudden collapse. The load introduction concept demonstrated a stabilizing effect on the beam structure.

Under cyclic loading up to 45 kN, the expected increase in the number of cycles to failure with decreasing load amplitude was observed. Notably, several specimens exhibited distinct hysteresis behavior prior to failure, including asymmetry and a progressive narrowing near the zero-crossing in high-cycle regimes. The specimen with the highest cycle count failed through a fiber break on the tensile side, suggesting a different failure mechanism compared to the quasi-static case.

These observations highlight the potential of hysteresis behavior as an indicator of internal damage, making it a promising approach for future structural health monitoring applications. Upcoming test series will focus on high-cycle regimes and will incorporate strain gauge measurements to further investigate the link between hysteresis characteristics and damage evolution. From a design perspective, the findings emphasize that fatigue failure may occur at locations different from those predicted by static analysis. Therefore, applying conventional safety factors to static designs may be insufficient for fatigue-critical CFRP structures. A more nuanced approach to fatigue assessment is needed – especially when mechanical connections are involved.

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