Design of the Load Introduction of Continuous Fibre-Reinforced Components for Cyclic Loading

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Abstract

The use of fibre-reinforced plastics (FRP) in structural components offers significant lightweight potential due to their high specific stiffness and strength. However, the complex fatigue behavior of FRP often leads to insufficient consideration of long-term strength during product development, which is typically compensated for by high safety factors. This study aims to explore additional lightweight potential by addressing fatigue phenomena more accurately, focusing on the critical area of load introduction. Bolted connections, commonly used for load introduction, are prone to bearing failure under cyclic loading. Therefore, a simplified design support for the load introduction in cyclically loaded FRP components is necessary.

Keywords

Fibre-reinforced Plastics, Lightweight Design, Fatigue, Load Introduction

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1. Motivation

Fiber-reinforced plastics (FRPs) have great lightweight potential due to their high specific stiffness and strength. In use, FRP components are often subjected to cyclic loading. Due to the complex fatigue behavior of the material, however, the fatigue strength behavior is usually inadequately considered in product development and is only compensated for by high safety factors [1, 2]. By taking fatigue into account in a more differentiated manner, additional lightweight potential can thus be unlocked. A particularly critical component area is the load introduction. In simple structures, load introduction often occurs via bolt connections, where hole-bearing failure can occur, especially under cyclic loading [3]. Therefore, an easy-to-implement design support is required for the load introduction of cyclically loaded FRP components.

Current approaches to the dimensioning of load introduction often rely on empirical methods that do not always consider the specific properties of FRPs. This leads to over-dimensioned components that are heavier and more expensive than necessary. A more precise analysis and consideration of fatigue phenomena can not only reduce the weight of the components but also increase their reliability and lifespan. Additionally, innovative load introduction concepts, such as the use of structured surfaces or optimized adhesive bonds, can improve the load-bearing capacity and fatigue behavior of the connections. Finally, the development of such concepts can enable the application of FRPs in more areas by making them more cost-efficient and high-performing [4].

2. State of the Art

When introducing loads into FRP bending beams, several key aspects must be considered to categorize the load introduction effectively. First, the mechanism of load introduction is crucial, which can occur through frictional contact, form-fitting, or adhesive bonding. The location of load introduction is also important: loads can be introduced into the flange, the web, or a combination of both. It is also possible to introduce loads through another structural element within the beam, such as a bulkhead. When introducing loads into a flange, the bending stress state must be considered, with compression being the most critical case. The use of load introduction elements depends on whether they are placed inside or outside the profile, as in the case of a bulkhead or patch [5]. Another consideration is the removability of the load introduction elements, which can be detachable, semi-detachable, or permanent. Finally, the type of load to be introduced must be considered, which can manifest as a point load, distributed load, moment, or couple. For point loads, further differentiation is possible between tensile or compressive forces acting perpendicular to the beam's longitudinal axis, leading only to planar bending, forces in arbitrary directions with or without eccentricity relative to the beam's centroidal or shear center axis, resulting in normal forces, torsional moments, and oblique bending either individually or in any combination, as well as a moving point of load application [5].

Load introduction in FRPs can be achieved in various ways, typically differentiated into adhesive (substance-to-substance), frictional (force-to-force), and form-fitting (shape-to-shape) connections. Each of these types has specific advantages and disadvantages, depending on the application area and requirements. Press and clamp connections are rarely used as methods for load introduction in fiber composite technology [6]. Therefore, this discussion will focus only on adhesive and form-fitting connections.

2.1. Adhesive bonds

Adhesive bonds are one of the most common methods for connecting FRP structures. This method allows for uniform stress distribution and minimizes local stress concentrations. Since FRP materials with thermosetting matrices already possess adhesive-like properties, the use of adhesive bonds is particularly advantageous [6]. Modern Finite Element Methods (FEM) enable detailed analysis and evaluation of the strength of adhesive bonds. However, simplified methods are still required for use in early design phases [7]. Specific challenges arise in considering the unique material properties, especially the low interlaminar shear strengths [6]. The design significantly influences the load-bearing capacity of adhesive bonds. Design guidelines for FRP adhesive bonds are oriented towards those for metallic structures [8]. The long-term behavior of adhesive bonds is critical, as temperature, humidity, and chemical influences can alter the properties of the adhesives. Long-term tests and aging studies are therefore essential to ensure reliability [9]. When executed optimally, adhesive bonds can achieve high fatigue strengths, as shown in studies on overlap joints. A sufficient overlap length is necessary to evenly distribute stress peaks within the adhesive layer. In fatigue tests, it is often the joined parts that fail rather than the adhesive bond itself [10].

2.2. Form-Fitting Bonds

Bolt connections are a common method for load introduction in FRP. These connections offer numerous advantages, including the possibility of disassembly, and the ability to transmit large forces. Bolt connections allow for direct load transfer through bearing stress, with the bolt introducing the force into the laminate. However, this leads to fiber breakage in the area of the hole, which can compromise the structural integrity of the laminate. Despite this potential weakness, bolt connections have proven effective in practice for force transmission [6]. The main failure mechanisms in bolt connections in FRP are shown in Figure 1.

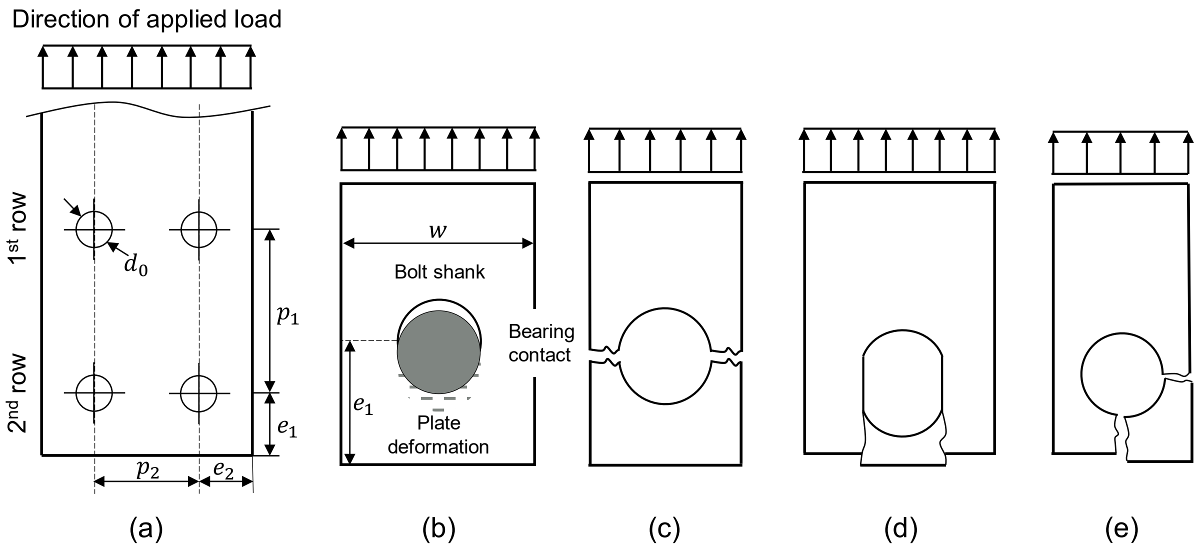

Figure 1: Geometry and failure modes of FRP plate-to-plate connections; (a) Connection geometry; (b) Bearing failure; (c) Net-tension failure; (d) Shear-out failure; (e) Cleavage failure; according to [11].

Bearing failure is a localized compression failure near the bolt, marked by resin crushing and fiber buckling. It is less brittle and more damage-tolerant, occurring with a high plate width-to-hole diameter ratio [12]. Proper geometry ($e_1/d_0 > 3$ and $\mathrm{w}/d_0 \geq 4$) helps ensure this desirable failure mode [13]. Net-tension failure happens with large bolts and small plate widths, leading to sudden transverse cracking. It is brittle and common in multi-row connections with small edge distances. Adequate edge distance is crucial to avoid this failure [11, 12]. Shear-out failure, a brittle tension-type failure, occurs with small end distances ($e_1/d_0 \leq 4$). It often follows bearing failure and is an in-plane mode. Hollmann provides theoretical models for this failure [12, 13]. Cleavage failure combines net-tension and shear-out failures, starting at the plate end. It occurs with short end and edge distances and high longitudinal fiber content. Ensuring proper distances prevents this failure [15].

To ensure the safety and load capacity of bolt connections, certain design considerations are necessary. The manufacturing of the holes must be precise to ensure fit and strength. Errors in drilling can create weak points that impair the connection's lifespan. The diameter of the bolts and the distances to the edges of the components must be sized to minimize stress concentrations and optimize load distribution. Insufficient edge distances can lead to premature failure [17]. Embedded metal foils or additional reinforcement layers around the holes can increase bearing strength and reduce the required edge distances [18]. Applying targeted clamping pressure on the joint parts increases the load capacity and reduces the tendency for interlaminar failure [19]. Selecting bolt materials with high strength and compatibility with FRP materials is crucial. Important criteria include corrosion resistance and mechanical properties.

3. Research Problem and Research Goal

A crucial prerequisite for the use of FRPs in structural components is a load introduction that meets the requirements of cyclic loading. The typical fatigue behavior of FRPs leads to high initial damage accumulation from microcracks, followed by a plateau known as the Characteristic Damage State (CDS) [20]. Once delamination begins, there is a rapid growth of damage until failure occurs. To avoid delamination and increase the reliability of the components, FRP components must be designed to reach the CDS without failure of the load introduction [21].

Against this background, the central research question of this project arises: How can load introduction in cyclically loaded FRP components be achieved so that the CDS is reached without the load introduction failing? This question is of crucial importance for improving the fatigue strength and reliability of FRP structures in practical applications.

A specific sub-question within this research problem concerns the increase of the coefficient of friction through surface structuring when transferring shear forces in FRP-steel press-fits [22]. Therefore, the suitability of structured surfaces for frictional load introduction in FRP components is investigated. This includes comparing frictional connections with adhesive bonds to identify their respective advantages and disadvantages, and to derive design guidelines for load introduction in FRP components. If press connections with structured surfaces prove to be suitable for cyclic loading, they offer the significant advantage of being detachable compared to adhesive bonds.

The investigation of structured surfaces as a method for load introduction aims to find alternative solutions to conventional adhesive bonds, potentially offering higher reliability and easier handling. The expected results of this research could lead to new design guidelines that improve the fatigue strength of FRP components and expand their use in cyclically loaded applications.

In summary, this research aims to develop new methods and guidelines for load introduction in FRP components used under cyclic loads. This involves both theoretical analysis and experimental investigations to validate the developed concepts. The insights gained are intended to enhance the performance and reliability of FRP structures in practical applications.

4. Methods and Procedures

To create design guidelines for load introduction in CFRP square profiles, a five-step approach has been developed, as shown in Figure 1. The approach is designed to systematically develop, test, and evaluate load introduction concepts to ultimately provide reliable and practical predictions for use in cyclically loaded applications.

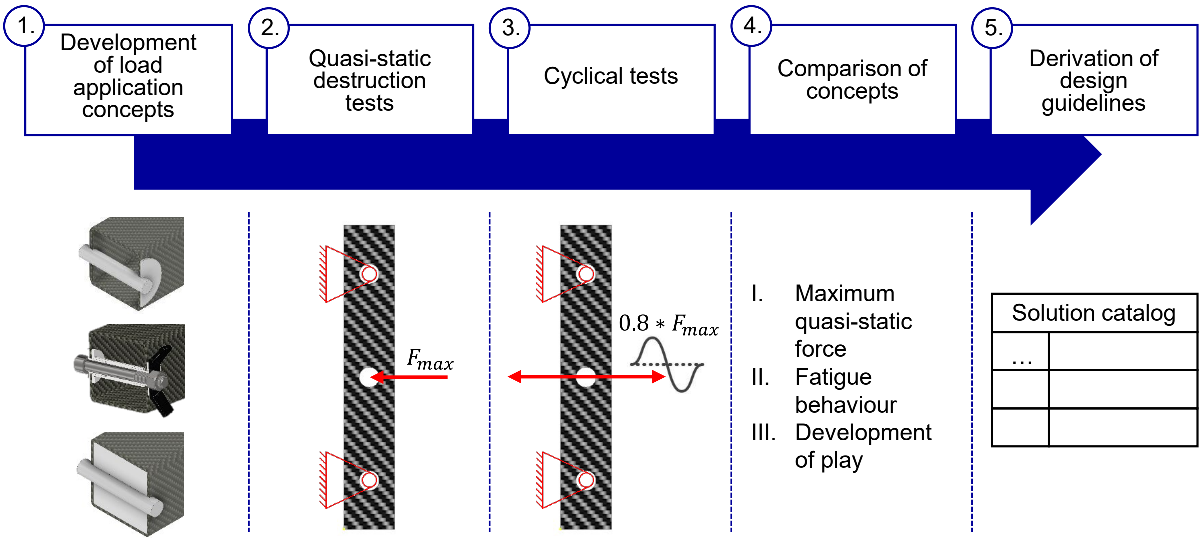

Figure 2: Approach for developing design guidelines for load introduction in FRP Structures.

Step 1 begins with a comprehensive literature review to identify and evaluate existing methods and solutions for developing load introduction concepts. A morphological box is then created based on this information, encompassing various dimensions and possible manifestations of load introduction elements. This tool facilitates the systematic combination and comparison of different concepts. Ultimately, the most promising approaches from the morphological box are selected and further detailed to assess their feasibility and performance.

During step 2, the concepts are subjected to quasi-static destruction tests aimed at determining their maximum load capacity. This maximum load not only serves as an initial benchmark but also as the basis for selecting the amplitude for the subsequent cyclic tests.

For step 3, cyclic testing is undertaken where a maximum amplitude of 80% of the previously determined maximum load is chosen to simulate realistic operating conditions. The selection of the number of cycles and the stress ratios considered is informed by existing studies on unidirectional test specimens. The objective is to reach the CDS without causing premature failure of the load introduction.

The evaluation of the concepts takes place in step 4, based on data from the quasi-static and cyclic tests. The concepts are assessed according to three main criteria. Static maximum force (I.): The maximum load capacity of the concepts under quasi-static loading. Fatigue behavior (II.): The fatigue behavior of the concepts under cyclic loading. Development of play (III.): The change in play within the connections during cyclic loading.

Finally, in step 5, recommendations for designing load introduction under bending stress are formulated. These recommendations are based on the collected test data and the evaluation of the concepts. The developed design guidelines are cataloged and made available for practical application in the design of FRP components under cyclic loading. This systematic approach ensures that the developed concepts are both theoretically sound and practically tested, focusing on optimizing load introduction to enhance the fatigue strength and reliability of FRP components.

5. Design of a Load Introduction for a 3-Point Bending Test

The design procedure for a load introduction was carried out on a ‘40x40 mm High Strength Carbon Fibre Epoxy Square Tube’ provided by the manufacturer CG TEC. This design aimed to evaluate the load introduction methods for a 3-point bending test setup.

5.1. Development of Load Introduction Concepts

Three concepts for batten insertion were developed. The simplest solution examined was an adhesive connection. In this case, the force transmission is realised by externally applied discs, which are fixed using 3M Scotch-Weld EC-9323-2 B/A. This adhesive is suitable for joining carbon fiber-reinforced plastics (CFRP) and metallic materials and is aerospace-certified.

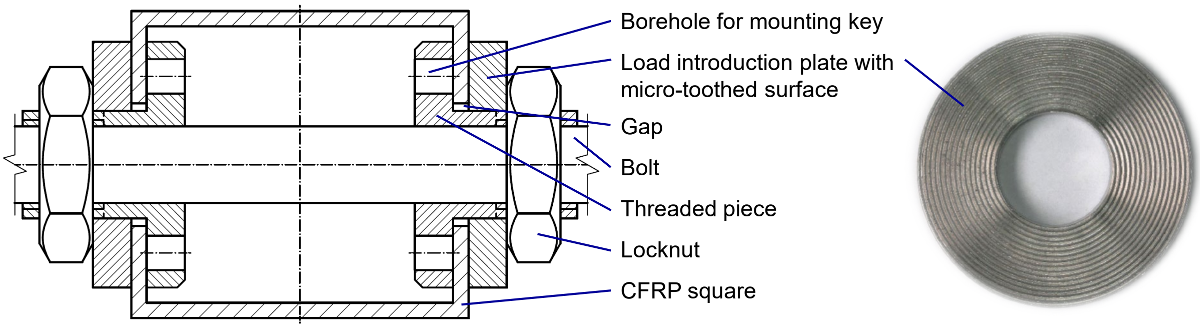

Figure 3: Design of the second concept - micro-serrated surface.

The second concept uses external discs with a textured surface created by flat spiral turning. The tooth height and the tooth tip angle were selected based on literature values in order to achieve an optimum static friction coefficient with permissible surface pressure. The contact surfaces were dimensioned identically to the first concept for better comparability. The structure of the load line is shown in Figure 2. One design disadvantage of this concept is that components have to be attached from the inside.

As a third concept, two C-sleeves are used to create a positive fit and thus ensure force transmission. The sleeves are bonded to the profile. This allows force to be transferred to the CFRP profile via both the webs and the belt.

5.2. Quasi-Static Destruction Tests

The tests were conducted on a Galdabini Quasar 100 material testing machine. The results of the quasi-static destruction tests are shown in Figure 4.

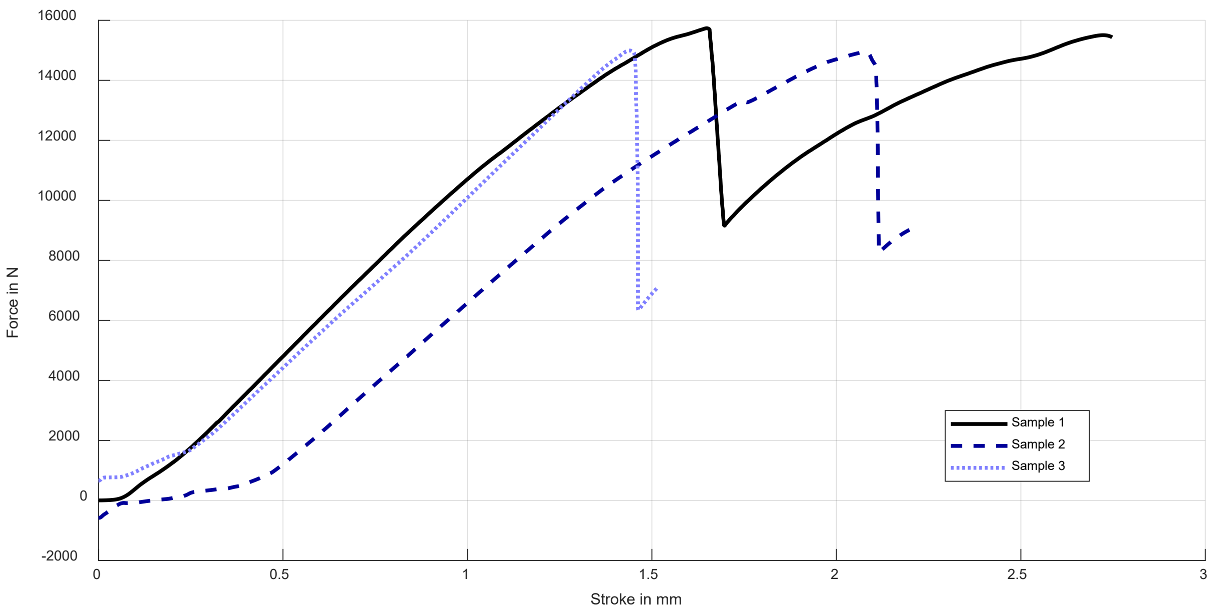

Figure 4: Quasi-static destruction tests of load introduction via adhesive bonding.

The adhesive bond achieves an average maximum stress of 23.8 MPa. This value is 82 % of the shear strength specified by the manufacturer. With the chosen circular adhesive area, the bond fails, resulting in the matrix and fibers being torn from the top layer. Additionally, a larger adhesive joint was examined, which resulted in plastic deformation of the CFRP square profile. Based on sample 1, after the initial failure of the adhesive bond, the load transfer through bearing stress can be observed. The graph shows that a similar force could be transmitted; however, bearing failure occurred. In sample 2, a settling behavior occurred in the test setup, which can be identified in the graph by the initially low slope.

In Figure 5, two failure images of load introduction using adhesive bonds are shown. In the upper image, the matrix has detached from the fibers, exposing the top fabric layer and tearing out individual fibers. In the lower image, adhesive failure to the steel disc is observed, with almost all of the adhesive remaining on the CFRP laminate. The image of the lower CFRP square belongs to Sample 2 from Figure 4, where the bearing failure at the hole is clearly visible.

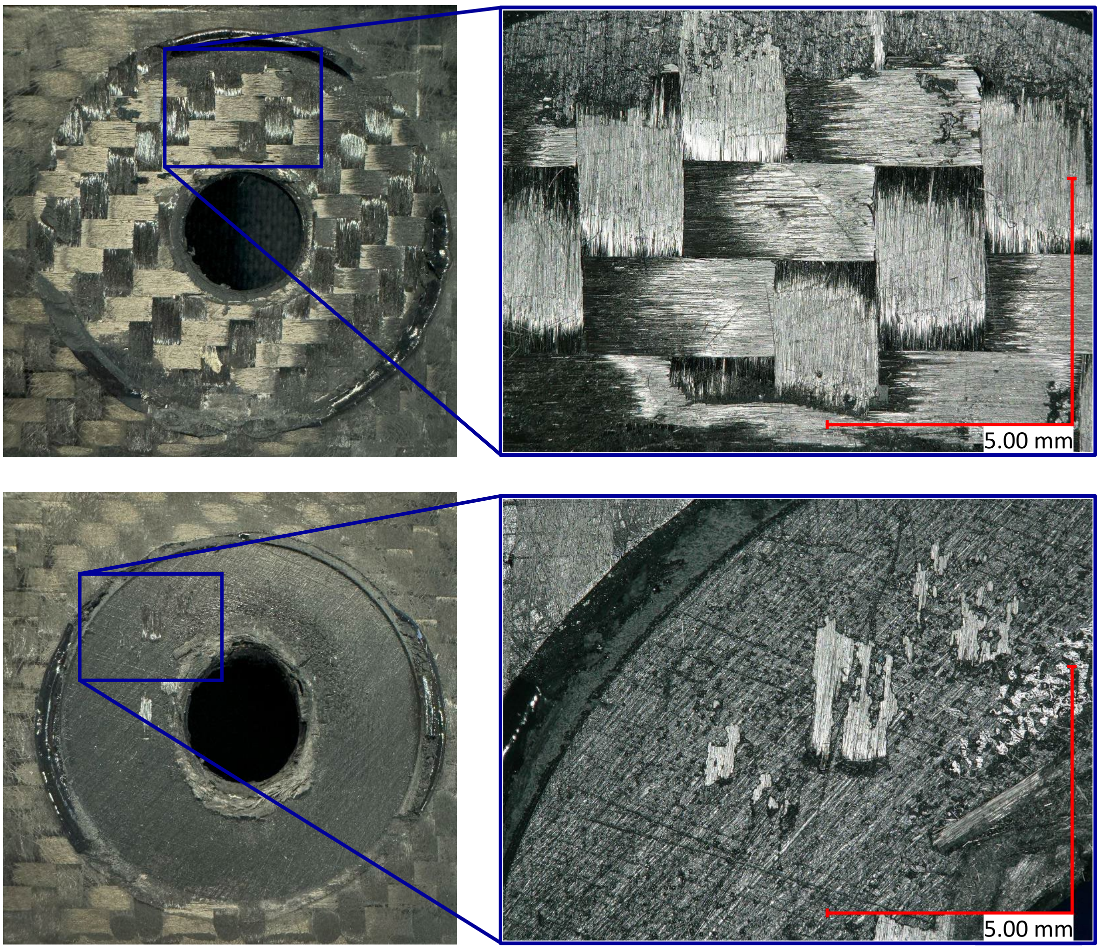

Figure 5: Failure of the load introduction. Above between fibres and matrix, below between adhesive and steel discs.

The second concept sustained an average maximum load of approximately 8.3 MPa. This value is significantly below the maximum load of the adhesive bond. The maximum force transmitted was about 30% of what can be transmitted through bearing stress. When the load introduction failed, there was a slippage of the contact discs, causing damage to the top layers of the laminate, as shown in Figure 5.

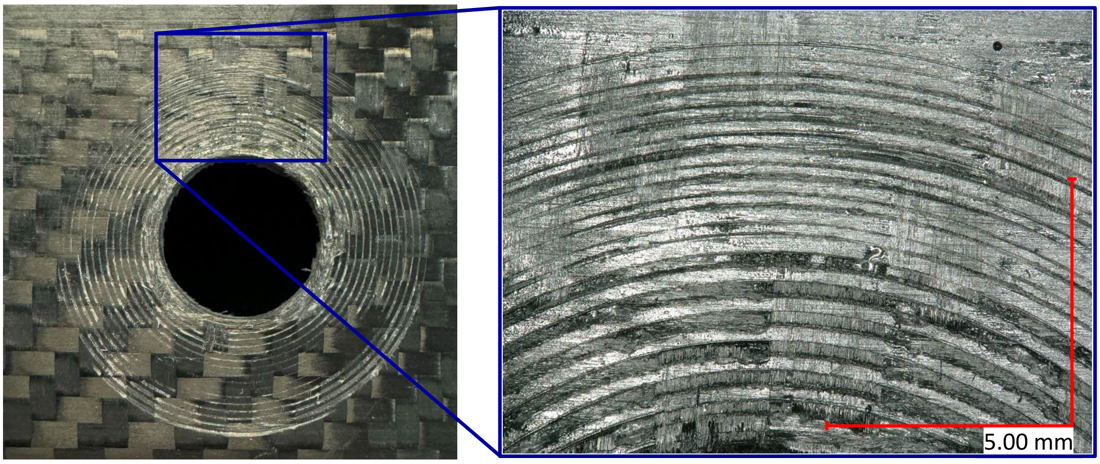

Figure 6: Surface of the CFRP sample after load transmission via micro-serrated surface.

In the magnified view, it can be seen how the profile was pressed into the CFRP material. In the immediate area of the hole, the exact profile of the contact disc is visible. However, in the outer area, the indentation depth decreases. This suggests that less force can be transmitted in this area. The micro-toothed contact discs were pressed with an application force based on literature values. A possible explanation for why the profile was not fully pressed into the CFRP square is that the discs may have bent. Another reason could be the geometry of the profile. Sharper-edged profiles with lower displacement volume could yield better results. In load introduction through micro-toothed surfaces, there is a combination of different types of force transmission – within the plane, force is transmitted both by frictional contact and by form-fitting. Therefore, by adjusting the profile to increase the surface area, an increase in the maximum transferable load can be achieved.

5.3. Cyclic Tests

In the cyclic tests, the load responses of the samples were examined over a predefined number of load cycles. Figure 6 shows the force-displacement curves of a sample with adhesive bonds for selected cycle numbers.

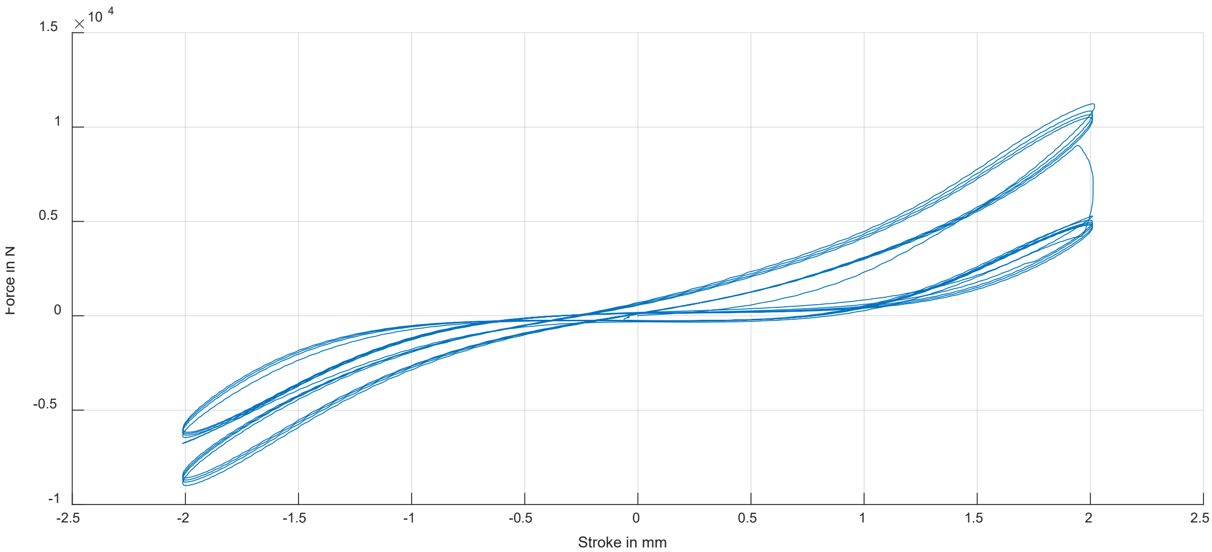

Figure 7: Hysteresis behavior of an adhesive sample with selected load cycles.

A typical hysteresis behavior is observed. This behavior is characteristic of materials under cyclic loading, where energy losses during the loading cycles are represented by the hysteresis loops. Notably, Sample 2 exhibits a significant drop in force after a certain number of cycles. This drop indicates the failure of an adhesive joint. After the adhesive bond failure, bearing stress takes over the load transfer, which is reflected in a changed hysteresis behavior. The newly established hysteresis loop shows that the load is now primarily introduced into the material via the bolts, altering the resistance and force distribution within the sample. Based on the sample, it was already apparent that bearing failure occurs even at low forces.

Bearing failure is considered a ductile and therefore predictable type of failure. This can be seen in the graph, as there was no significant decrease in strength after the adhesive bond failure. However, it also shows that simple bearing connections with bolts are not suitable for all applications. On one hand, the transferable forces are far below the allowable loads of the material; on the other hand, there are applications where no development of play is permissible. This leads to the conclusion that other load introduction concepts, such as the adhesive bond or the connection with micro-toothed surfaces presented here, may have a design advantage. Since the failure behavior—especially with micro-toothed surfaces—has not been thoroughly researched yet, further investigations are necessary.

6. Summary and Outlook

The quasi-static and cyclic tests conducted provided crucial data on the maximum load capacity and fatigue behavior of the connections. It was shown that with a sufficiently large adhesive surface area, external adhesive bonds are adequate, leading to plastic failure of the CFRP component in a 3-point bending test. The results highlight the importance of proper dimensioning and selection of load introduction concepts to ensure the long-term reliability and performance of FRP components. For example, it has been shown that simple bolt connections exhibited early signs of bearing failure even at low load cycle counts and force amplitudes. The insights gained can be used to catalog load introduction principles in a solution catalog for predefined load scenarios. Based on the results achieved, further investigations are planned to validate and optimize the developed concepts and design guidelines.

The next step is to optimize the concept of micro-toothed discs. In the following tests, discs with an adapted profile geometry will be tested. A milled pyramidal profile can create sharper teeth, and this profile type also has a lower displacement volume. The third advantage lies in the increased surface area of the profile, allowing for the transmission of higher forces. If the micro-toothed discs prove to be suitable for loads under cyclic conditions, they offer many advantages in application. Unlike common adhesive bonds, these are removable connections. Additionally, the assembly is significantly less labor-intensive.

To further investigate the suitability of the existing and other load introduction concepts, additional test series will be conducted. These tests will also examine different loading situations. Due to the inhomogeneity of FRP materials, the type and direction of the load are essential for design. This inhomogeneity also affects the load introduction, requiring that the type of load be considered at the beginning of the load introduction design.

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