INVERSTIGATION ON THE FAILURE MECHANISM OF COMPOSITE FASTENERS WITH COUNTERSUNK HEAD IN FATIGUE LOADING

M. Schuett[a*], H. Wittich[a], F. Nussbaeumer[c], K. Schulte[a,b] and B. Fiedler[a]

[a]*Institute of Polymers and Composites, Technische Universität Hamburg-Harburg, Denickestr. 15, 21073 Hamburg, Germany, Germany*
[b]*Department of Physics, Faculty of Science, King Abdulaziz University, Jeddah, Saudi Arabia*
[c]*Bishop GmbH Aeronautical Engineers, Hamburg, Germany*
**martin.schuett@tuhh.de*

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Abstract

This experimental study presents a detailed study on the failure mechanisms of a CFRP single-lap shear joint under cyclic loading conditions. The joint consists of two laminate plates and two CFRP fasteners with countersunk heads. Based on the investigations of this experimental work, the failure mechanisms in cyclic loading of the CFRP-fastener can be described. Further test with different parameter configurations show their influence on the failure process of the joint.

1. Introduction

In aircraft industry bolts – made of steel or titanium – are widely used in order to join CFRP structures. They are removable and permit to gain access to the interior of the structure for inspection or repair purposes. However, the holes in the structural components lead to a stress concentration and the large number of fasteners results in a weight penalty. Additionally the difference in the electrical potential conductivity between the composite laminate and the metallic bolts results in a problem of galvanic corrosion [1, 2]. In order to overcome weight and corrosion problems of the metal fasteners, the idea of using fasteners made of composite materials arose.

In the literature only little information can be found on this type of fasteners. R. Starikov and J. Schön studied the quasi static and fatigue behaviour of titanium and composite fasteners [2, 3]. They found that titanium fasteners perform better than CFRP quasi-statically, but they lose their strength much faster under fatigue: at 10^6 cycles, composite and titanium fasteners fail at the same maximum stress level.

Reworked designs and production process of the CFRP fasteners in the recent years, suggest that the composite fastener has improved [10, 11, 12]. This leads to a much wider field of application. Therefore a deeper understanding of the failure mechanisms in static and fatigue loading is essential. Detailed investigations on composite bolted joints, describe their failure processes in response to several key features such as clamping force, coefficient of friction, clearance/fitting tolerance, joint geometric details and laminate lay-up [4, 6, 7]. In addition, secondary bending in a single lap joint and bending of the bolt create a non-uniform contact stress distribution between the bolt and the borehole edge. The result is a shear and tension force on the bolts [1, 2, 7, 8 and 9].

For composite bolted joints in general four basic failure modes can be observed: bearing, shear out and bolt failure. Whereas for two CFRP-plates joined with CFRP-bolts tested in a quasi-static load case, slight different failure modes are detectable. For a pure CFRP-joint bearing damage occurs in the laminate. For the failure of the CFRP-bolt three different failure modes can be detected due to the combined load case of shear and tension: inter fibre failures in the contact area of the two laminate-plates, a shear of the countersunk head from the bolt and inter fibre fracture starting from the tooth flank after the first pitch [10].

The literature overview has shown that the failure process for composite bolted joints with steel or titanium fastener system is described in detail already [2-9]. Based on these research results cyclic load tests with single lap shear specimens are performed to describe the failure mechanisms of the CFRP-fasteners in detail.

2. Experimental methods

2.1. Materials and geometry

Single lap shear (SLS) tests, based on ASTM D 7248, are performed using two bolts [12]. The composite plates are manufactured from carbon fibre/epoxy material system (T800S-M21) with quasi-isotropic layup $[45/90/-45/0]_{2S}$. The nominal ply thickness is 0.19 mm. The thickness of the CFRP-laminate is $h = 3.04$ mm. The geometries for the two specimen configurations follow the ASTM D 7248 (Figure. 1). The dimensions of the specimens are related to the diameter *d* of the bolt. For the experiments the nominal shank diameter is $d = 4.8$ mm. The width of the test specimens is set to $w = 30$ mm. Jaws clamp the test specimen at its ends and apply the cyclic loads. Taps ensure an optimal load transmission into the specimens from the clamping system. A doubler to each grip avoids eccentric loading. The holes in the test specimens are drilled with countersink drillers from the company Klenk. A patented fibre cracker on the drilling tool and distinct drilling parameters are taken, to minimize delamination, chip-out fibres and degradation of matrix due to overheating in the bore edge [1].

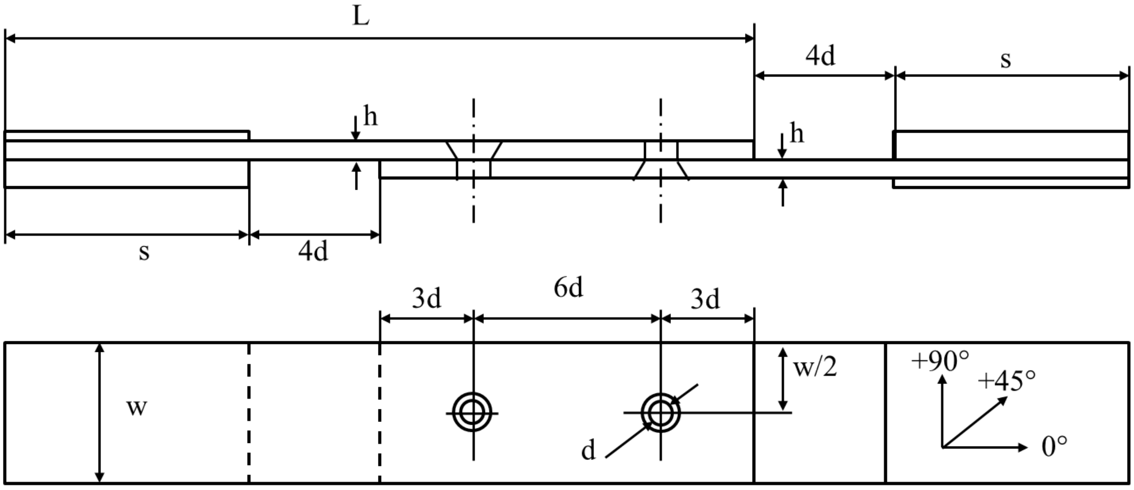

Figure 1. Specimen geometry for two bolts, all dimensions are in millimetre [mm].

The fastener-systems tested in this work is the CFRP-bolt (IM7/Peek) with countersunk head, shank diameter d = 4.8 mm, manufactured in close collaboration with the Swiss company IcoTec (Figure. 2).

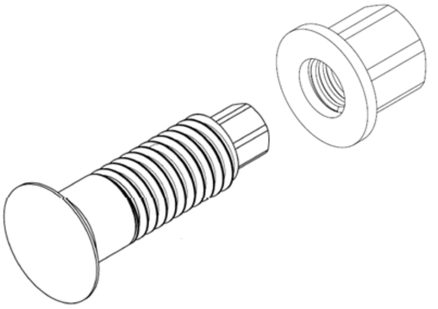

Figure 2. Specimen geometry for two bolts, all dimensions are in millimetre [mm].

2.2. Materials and geometry

The specimens are tested in fatigue with the stress ratio $R = \sigma_{min}/\sigma_{max} = 0.1$ using a cyclic load testing machine from the company Instron. The test frequency was set at 5 Hz to minimize the thermal degradation effects caused by the friction between the two laminate plates. All experiments were performed at room temperature (≈22°C) and ambient relative humidity.

For this experimental work fatigue tests are performed with two parameter configurations:

- Two different clamping forces resulting from fastening torques of 1.5 Nm and 2 Nm
- Three different Fitting tolerance / Clearances –
    - interference fit with a bore hole diameter of D = 4.7 mm
    - transition fit with a bore hole diameter of D = 4.8 mm
    - clearance fit with a bore hole diameter of D = 5 mm

To measure the influences of the different parameters on the failure process, several extensometers are mounted in order to record the displacements from the several components of the joint. During the cyclic load tests the global elongation of the specimens and the heating of the specimen surface are monitored.

In order to characterize the failure process of the CFRP-bolt, acoustic emission (AE) is recorded. R. Gutkin et al. point out that peaks in the AE curve of a CFRP-laminate under load correspond to the occurrence of damage [7]. Consequently, tests are stopped and scans of the microstructure are analysed for certain acoustic events in order to characterize the evolution of the failure process until breaking. For a further detailed inspection of the failures investigation methods such as Ultrasonic C-scans, X-Ray scan, light and electron microscopy are performed.

3. Results and Discussion

The bolted joints with the different parameter configurations are tested at different load levels determined from previously conducted quasi-static tensile tests [10]. For each F-N-Curve (Force versus Number of cycles diagram) at least 10 specimens are tested in cyclic loading. The results are displayed in Figure 3 and Figure 4. In order to compare the failure mechanisms for the different specimen configurations the maximum failure force is chosen to determine the load levels at which the fatigue test are performed. Consequently it has to be assumed that the diameter of the bore hole and the geometry of the fasteners are ideal with no tolerance due to the production process. The lines in the figure are a linear fit of the logarithmic fatigue data.

Due to the behaviour of a bolted joint, different tightening torques, result in different clamping forces in the joint. A high fastening torque results in a high clamping force and vice versa. As the results in Figure 3 indicate, SLS specimens mounted with CFRP-fasteners using a torque of T_1 = 1.4 Nm have a higher fatigue resistance then specimens mounted with a torque of T_2 = 2.0 Nm.

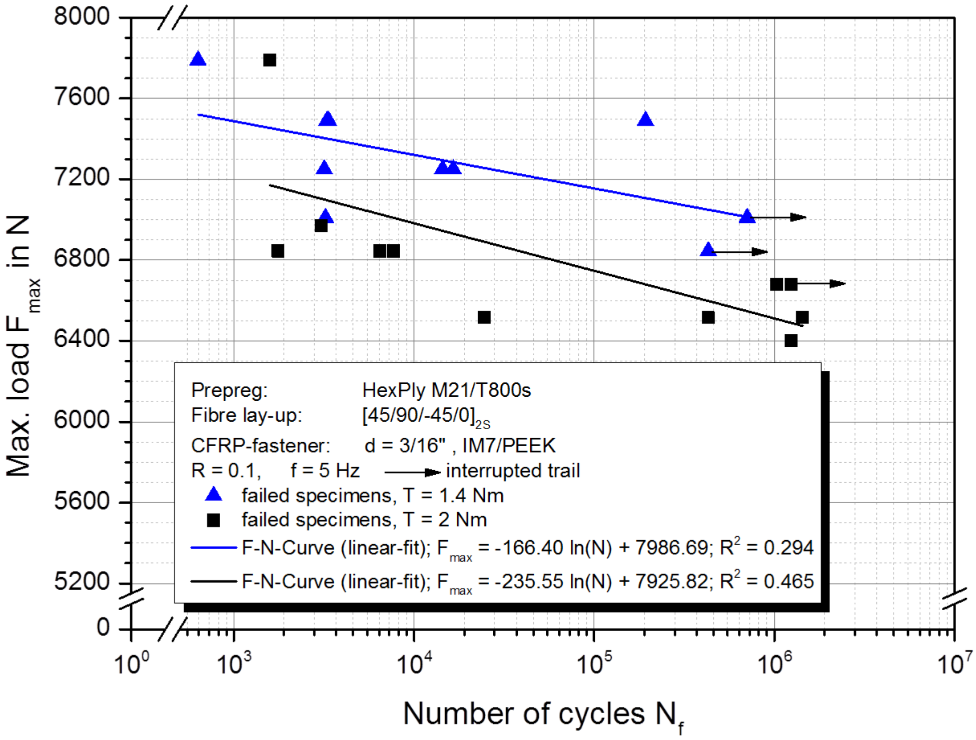

Figure 3. Influence of the clamping force on the fatigue life for SLS-specimens with CFRP-fasteners mounted with torques of T_1 = 1.4 Nm and T_2 = 2Nm.

A possible explanation for the differences in the fatigue resistance could be the fact that a higher torque causes higher axial force in the bolt. Furthermore applying an external load on the SLS-specimen results is secondary bending of the specimen [6]. This effect induces besides the shear force also a tension force into the bolt. The overlap of these two axial forces in the fastener could take influence on the finale failure.

For both specimen configurations, a big mean variation of the fatigue resistance on single load levels is observable. The distribution of the data points for the specimens with the lower clamping force (T_1 = 1.4 Nm) is higher than that for the specimens with the higher clamping force (T_2 = 2.0 Nm). This is also indicated by the R-value of the linear fit.

For further investigation of bolted joint a fastening torque of T_2 = 2.0 Nm is chosen in the following test programme. In Figure 4 the influence of the clearance on the fatigue life for three different sets of fitting tolerances of the joint for the SLS-specimens is displayed. As can be seen the specimens with a clearance fit have a higher fatigue resistance then that specimens with a transition fit. The fatigue resistance for the test coupons with the interference fit is the lowest.

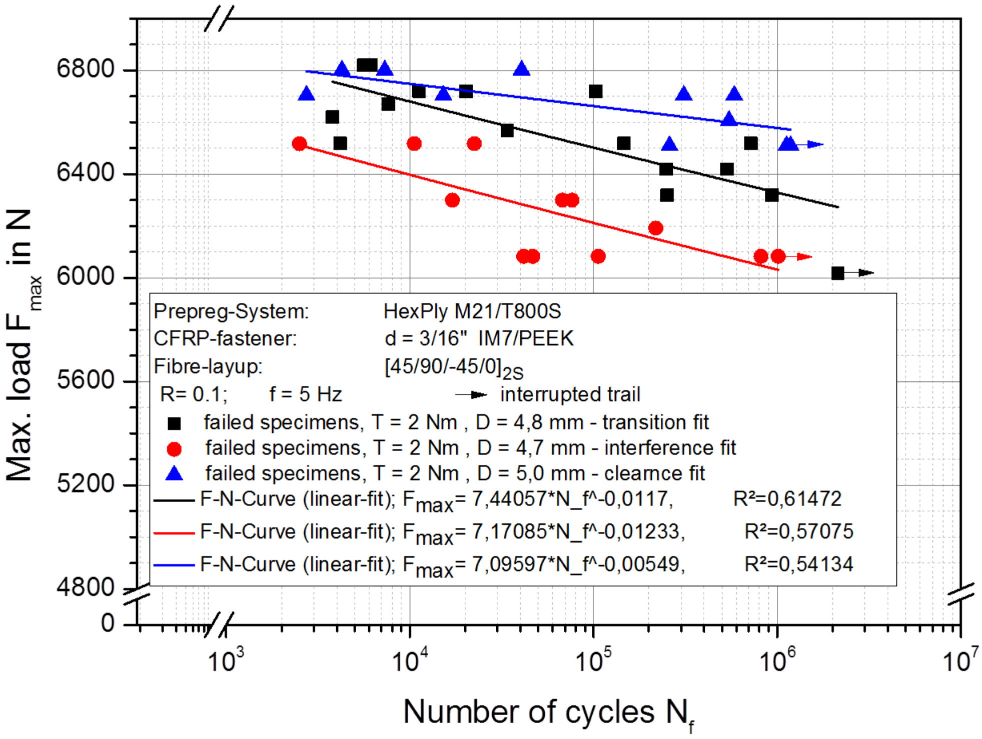

Figure 4. Influence of the clearance on the fatigue life results for SLS-specimens with three different sets of fitting tolerance: transition fit, interference fit and clearance fit

During the fatigue test programme the finale failure of the specimens is a failure of the bolt. However, different failure modes independently of the parameter configurations of the SLS-specimens can be detected. In the laminate plates bearing damage can be observed for each test. Whereas the bearing for the specimens tested with an interference fit was smaller than that in other test configurations. The failure mechanisms which could be observed for the bolt are, inter fibre fracture in the thread and a shear of the countersunk head from the shaft. Furthermore, in the contact of the two CFRP-plates, fibre and inter fibre failure can be observed.

4. Conclusions

This paper presents an investigation of the failure process for a SLS-test specimen in cyclic loading. Based on the investigations, several conclusions can be summarized for the fatigue behaviour:

- A smaller mounting torque which subsequently results in a lower clamping force, leads to increase of the fatigue life span for SLS-specimens tested on the same load level
- The influence of the fitting tolerance of the joint in fatigue life shows that a clearance fit exceeds the life time in comparison to a transition fit. A interference fit in contrasts leads to the lower life time prediction for a pure CFRP joint

For all parameter configurations of the test specimens under the cyclic load conditions the following failure mechanisms are to be observed:

- Inter fibre fracture are observed in the thread of the CFRP- bolt.
- Shear of the countersunk head

- Fibre and Inter fibre failures in the CFRP-bolt shaft in the cross section of the contact area of the two CFRP-plates.
- A combined load case of shear and tension on the CFRP-fastener lead to the finale failure of the SLS-specimens.

Further test especially with different parameter configurations will be performed to see their influence on the joint.

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