Numerical Investigations of Adhesive CFRP-Joints and Determination of Transverse Properties of the Adherends

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Abstract

Within the DLR (German Aerospace Center) project “Next Generation Car” adhesive joints of carbon fiber reinforced polymers (CFRP) are investigated. The focus was set on a numerical model to predict the failure mode (surface ply failure, delamination or adhesive failure) depending on the stacking sequence of the laminate. In a first step, the ‘five-point bending’ test was evaluated and chosen to measure the out-of-plane shear strength of a woven fabric and unidirectional CFRPs with various fiber angles. The results from the Digital Image Correlation (DIC) were compared to analytical and numerical models. An evaluation routine was derived to assess the out-of-plane shear properties of the CFRP. Finally, fine discretized numerical models of single-lap joint (SLJ) specimens were discussed and compared to tests.

1 Introduction

Due to the increasing use of multi-material design and fiber-reinforced plastics (FRP) for weight reduction of body in white, new bonding technologies are needed in the automotive industry. In the last years the number of adhesive joints in cars was significantly increased, leading to a need for design guidelines.

Many recommendations for adhesive joints with fiber reinforced adherends can be found in the literature, but only very few approaches can predict the failure mechanism by calculations. For example, tapered adherends and fillets are supposed to lower the peel stresses in composite joints [1], [2]. Some of the investigations are even contradictory e.g. the influence of the surface-ply orientation [3], [4].

The main difficulty for a reliable prediction lies in the complex failure modes of laminates compared to monolithic materials. In Fig. 1 the most important failure modes are shown. Similar to metallic adherends, the bond can fail in the adhesive (cohesive failure) or at the surface between adherend and adhesive (adhesive failure). Furthermore delamination/ply-failure can occur in fiber reinforced adherends.

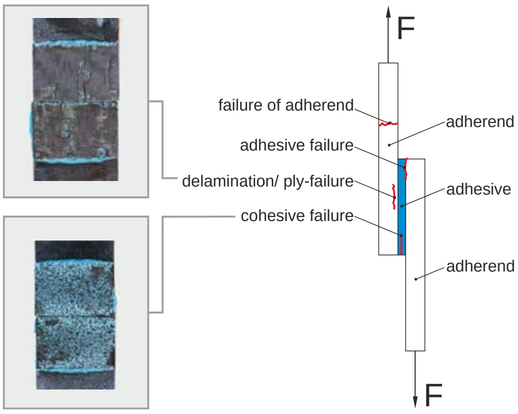


Fig.1: Failure modes of an adhesive bond of laminates.

A fine discretized model was set up to investigate which material parameters determine whether the adhesive or the adherend fails. A layer of cohesive elements represent the adhesive and each layer of the adherend is modeled by three solid-elements, Fig. 2.

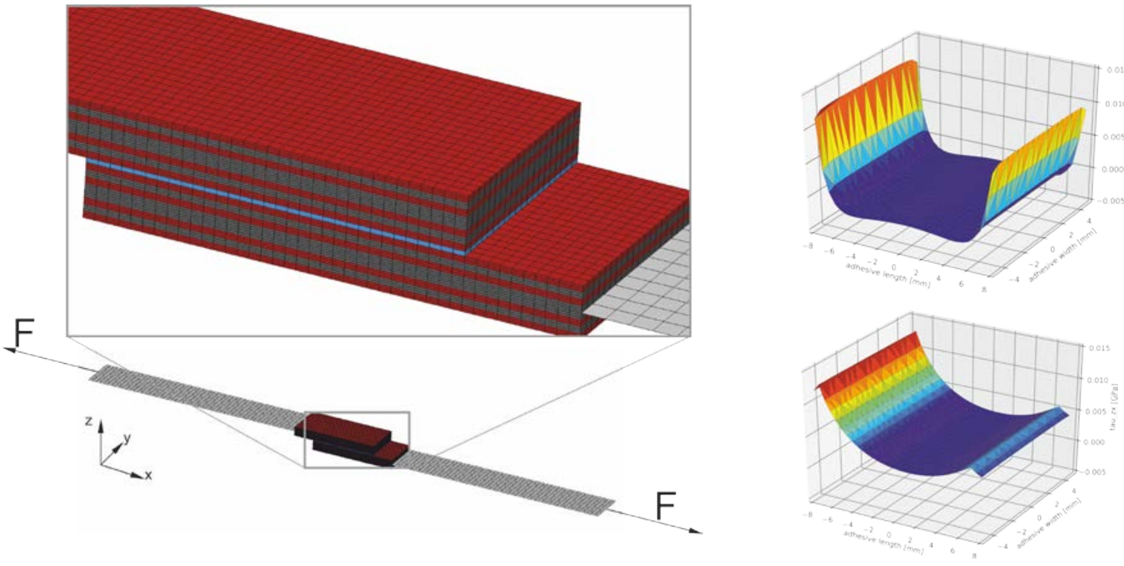
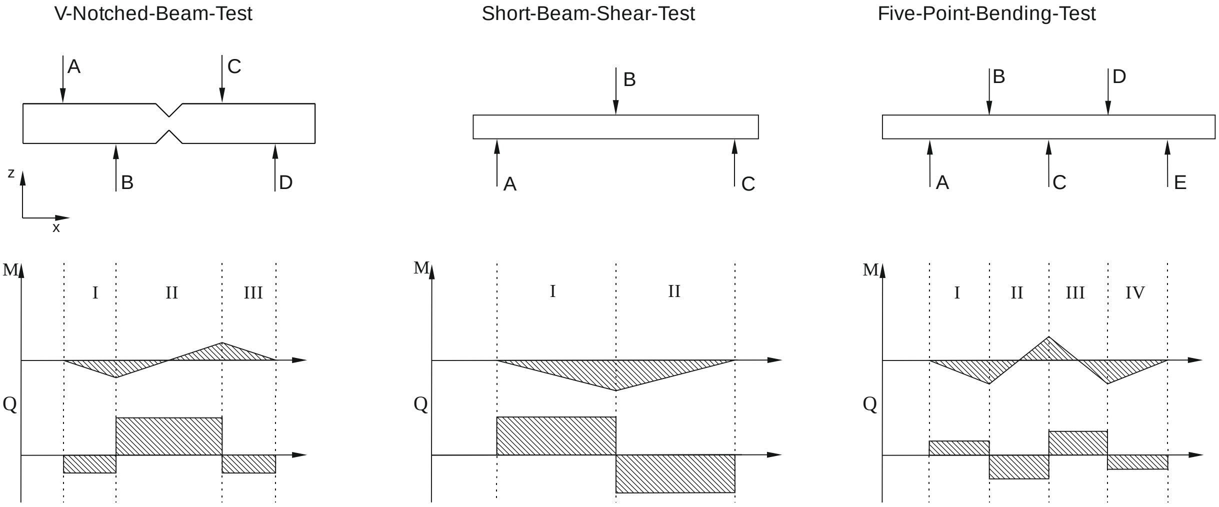


Fig.2: left: model of the single-lap-joint test, right: tensions

On the right side of Fig. 2 the calculated peel stresses in z-direction σ_z and the out-of-plane zx-shear stresses τ_{zx} in the surface layer of solids exactly above the adhesive are plotted. The plots show that all out-of-plane strengths are needed to predict the failure mode. A method is presented in the following paragraph to determine the shear-strength $\tau_{31,max}$ and $\tau_{23,max}$ for the single-layers.

2 Measurement of out-of-plane shear properties

Many different test methods are known in the literature to determine shear strengths [5]. Following, the 'V-Notched-Beam'-Test (VNB), 'Short-Beam-Shear'-Test (SBS) and 'Five-Point-Bending'-Test (FPB) are discussed. In Fig. 3 the distribution of momentum and force for the different tests are shown.


V-Notched-Beam-Test

Short-Beam-Shear-Test

Five-Point-Bending-Test

Fig.3: V-Notched-Beam-Test, Short-Beam-Shear-Test and Five-Point-Bending-Test

The VNB-Test (also known as Iosipescu-Test) is a standardized test method (ASTM D5379) and test results are reliable [6]. Disadvantages of this test are the difficulty to manufacture specimens and

complex test devices. A thick specimen is needed and the notches can pre-damage the specimen. The Double-Notched-Shear-Test and the V-notched-Rail-Test have similar disadvantages.
The SBS-test (ASTM D2344) is also a standardized test and the specimens are simple to manufacture. Disadvantages are the wide scatter of the results [7]. All these disadvantages are unknown for the FPB even though it is not standardized. It measures higher strengths with less variation than the SBS but the specimens are as simple as the SBS-specimens [7]. In Fig. 4 the DLR-Version for the FPB testing device is shown.

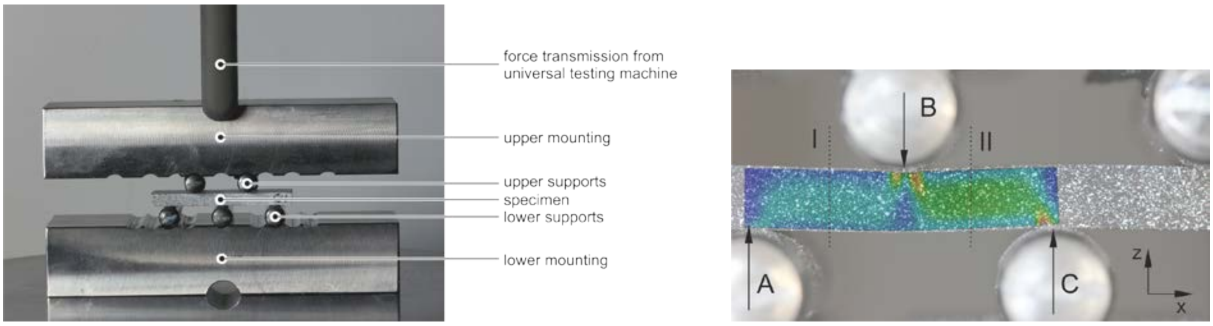


Fig.4: DLR-design of the FPB testing device, DIC with integration paths

The tested specimens were made of a woven fabric carbon-epoxy prepreg (SGL carbon fibers/ E210) and a unidirectional carbon-epoxy prepreg (SGL carbon fibers/ E022). The tested laminates are listed in Table 1. All specimens failed in the sections where the highest shear-stresses are expected (in the sections II and III and in the middle-plane of the specimen).

	l × w × h [mm]	**Av. max. load [kN]**	**Coef. of var. [%]**
$[0°]_{11}$	40 × 10 × 3.19	7.08	0.8
$[90°]_{11}$	40 × 10 × 3.19	1.24	1.8
$[(0°)_4\,(90°)_3\,(0°)_4]$	40 × 10 × 3.35	5.68	2.1
$[(0°)_4\ \ [(0°/90°)_F]_4\ \ (0°)_4\ ]$	40 × 10 × 3.35	6.73	1.4

Table 1: Results of the Five-Point-Bending tests

It is assumed that there is no parabolic distribution of the tensions through thickness and that the forces at the supports depend on the thickness and on the distance between the supports. A digital image correlation (DIC) analysis with *GOM-Correlate* was performed to measure the shear strains and calculate the forces and stresses.
To ascertain the forces F_A and F_C for the $[0°]_{11}$ and $[90°]_{11}$ at the lower supports, the strains in section I and II are compared to each other in formula (1) by integrating the strain along the paths shown in Fig. 4. The sum of all forces at the supports is equal to the measured force F of the universal testing machine.

$$\frac{\int_z \varepsilon_{zx,I}\,dz}{\int_z \varepsilon_{zx,II}\,dz} = \frac{F_A}{0.5F_C} \tag{1}$$

With the results and formula (2) the G-modulus were calculated.

$$G_{zx} = \frac{\frac{F_C}{2b}}{2\int_z \varepsilon_{zx}\,dz} \tag{2}$$

The laminate $[90°]_{11}$ failed due to bending. Outer 0° layer as in laminate $[(0°)_4\,(90°)_3\,(0°)_4]$ prevent this problem. A numerical investigation with G_{zx} from the first two laminates was performed to get the strength in 23-direction of the unidirectional layer. In Fig. 5 the results of the simulation are shown.

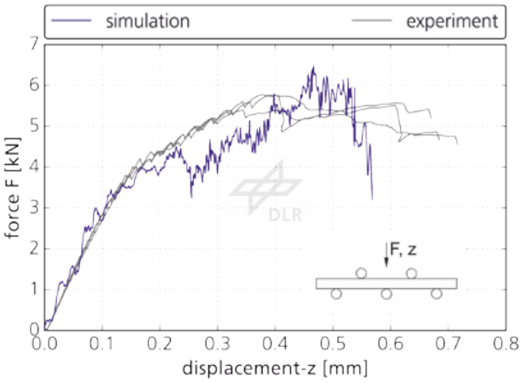


Fig.5: Results of the simulation with $[(0°)_4\,(90°)_3\,(0°)_4]$ compared to the experiments

The analytical ($\tau_{max,31}$) and numerical ($\tau_{max,23}$) results for the strengths of the single-layers are listed in Table 2.

	$\tau_{max,31}$ [GPa]	$\tau_{max,23}$ [GPa]
SGL carbon / E022	0.16	0.031
SGL carbon / E210	0.080	0.080

Table 2: Shear-strength of the single-layers

3 Numerical Investigations of Adhesive CFRP-Joints

A numerical model of a Single-Lap-Joint Test (SLJ) was set up to show that the results from Paragraph 2 can be used to predict the failure mode of the adhesive bond between two CFRP-adherends.

The geometry of the specimen is shown in Fig. 6. MAT261 was used for the single layers of the substrate and MAT240 for the cohesive-elements which represent the adhesive. The ends of the adherends are modeled by layered shell-elements to reduce the duration of the calculation. The layer-setups are $[(0/90)_F\ 0\ 90\ 0\ 90\ 0]_s$ and $[90\ 0\ 90\ 0\ 90\ 0]_s$. The material properties of the adhesive BM1496 were taken from earlier investigations by *M. Brodbeck* [8] and the parameters of the substrate from the datasheet [9] and from Paragraph 2.

Fig. 6 depicts the numerical results for both set-ups. The results obtained with the laminate including the fabric surface layer correlate with the experimental curves. Experimentally and numerically, a cohesive failure is observed. The slight higher displacements measured in the tests compared to numerical results are due to sliding between the clamps and the specimen, which was not taken into account in the numerical model.

The 90° surface layer (UD) failed in the second laminate at an earlier stage. This agrees with literature results reported in Paragraph 1, where failure in the laminate was observed for 90° UD-layers.

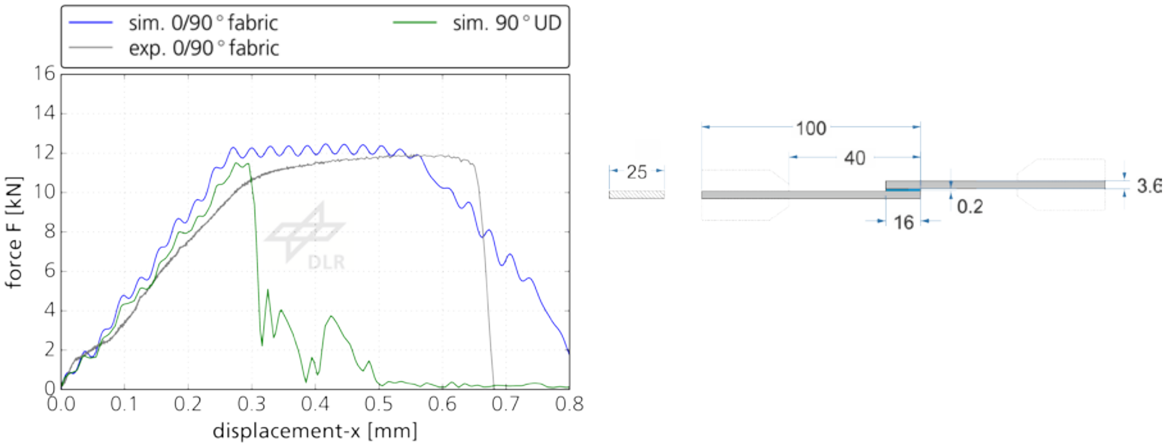


Fig.6: Simulation of SLJ and comparison to real experiment

4 Summary

Bonded joints with carbon fiber reinforced plastic (CFK) composites are more complex than those with metal partners. This is mainly due to the complex structure of laminates that can lead to different failure phenomena (intra- and interlaminar) in the joining region. In the literature, these phenomena have been investigated and parameters described which influence the failure phenomena. However, all the knowledge for the so-called ‘out-of-plane' stresses in laminates can still be described as incomplete. Furthermore, the results concerning the determination of the strengths are partly contradictory in the literature and the tests carried out for the methodical design of adhesively bonded joints are considered as not sufficient and inefficient.

The aim of this investigation was therefore the development or the selection of a test methodology, in which the strength-determining influences of CFK laminates in the area of adhesion can be measured with. It has been shown that the out-of-plane shear strengths are necessary in the calculation of CFK fillings. The so-called ‘Five-Point-Bending’-Test (FPB) has been identified as the most appropriate test method from a variety of numerically tested test devices and test assemblies. It has up to now the greatest potential for determining the inter- and intralaminar shear strength of (CFK) laminates with regard to the obtained strength values and the reached reproducibility. A calculation methodology was presented for this test method.

A FPB device was designed and manufactured in a special DLR design. One focus of the work was on the evaluability of the test results since the essential processes take place in a very small area (<< 1 mm). In the experiments, it was shown that internal stresses can be derived from the external forces as long as no pronounced non-linear behavior occurs. The experiments showed a high reproducibility, so that it stands out against other test methods. Also, the FPB test is uncomplicated in sample preparation and execution. The digital image correlation has shown great potential to determine the exact moment of damage and to correctly interpret the force-displacement curves.

The determined parameters were used to simulate a single-lap-joint. It was found that a 90° surface layer causes a failure in the outer layer, whereas in the case of a fabric as outer layer, the failure occurs in the adhesive layer. This also coincides with the literature sources discussed.

The advantage of the high-resolution model is the little effort to test many different combinations of substrate materials, stacking sequences and adhesive.

The next step will be the identification of a test method to measure the out-of-plane normal strength and to verify the method for more laminates.

5 Literature

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