DIRECT ADHESION OF CFR-THERMOPLAST ON STEEL – TESTING AND SIMULATION OF THE LAP SHEAR FRACTURE

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Abstract

In this work a novel joining technology by direct adhesion of carbon fiber-reinforced thermoplastic (CFRTP) with polyamide 6 matrix on steel is investigated. Based on endless fiber-reinforced thermoplastic tapes a unidirectional layup is manufactured with the FiberForge RELAY®. Here, the layup is stacked by ultrasonic welding points and is so far not consolidated to a laminate. Two preforms are positioned into a tooling with a metal sheet in between. Afterwards the joining process is carried out by applying heat and pressure on the tooling.

The manufactured hybrid double lap joint specimens are conditioned according to the standard DIN EN ISO 1110. Then, tension tests are performed evaluating different surface treatments on the metal sheet in terms of joint strength. Here, joint strength up to 19 MPa is achieved. Based on these results one of the surface treatments is characterized by DCB and ENF tests to get the energy release rates in Mode I and Mode II, respectively. These values are used as input parameters for the cohesive zone modeling of the interface in Abaqus. Finally the double lap joint tension test is simulated and shows a good correlation with the test result.

1. Introduction

Increasing demands on performance and costs of lightweight structures lead to combinations made of fiber-reinforced plastics (FRP) and metal, to hybrid materials and/or structures. One suitable method is selectively reinforcing a conventional metal structure by bonding locally a FRP patch based on structural performance. To enable this hybrid structure the joining plays a crucial role.

Mechanical bonding methods like screwing or riveting are not material-oriented, because they lead to stress concentration around the holes and result in additional weight [1]. Especially composites with thermoplastic matrix systems have limited suitability in adhesive bonding. One possible joining technology for thermoplastics with metal is the direct adhesion by using the meltability of thermoplastics. In [2] the direct adhesion is investigated with unreinforced and short fiber reinforced thermoplastics and metal. Here, the metal is heated up over the melting temperature of the thermoplastic part. Afterwards the thermoplastic is pressed on the heated metal. By cooling down the joint is realized.

In this work the direct adhesion is experimentally investigated with endless carbon fiber-reinforced thermoplastic (CFRTP) and steel. Before adhesion the CFRTP is in a preform condition out of several tape layers and not consolidated to a laminate. The consolidation of the preform is performed simultaneously with the joining. For this reason only one process step is needed to manufacture the CFRTP and to join with the metal part.

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2. Experimental

First, double lap joint (DLJ) tensile tests are carried out to compare the surface treatments by means of joint strength. Afterwards one surface treatment is characterized by double cantilever beam (DCB) and end notched flexure (ENF) tests to determine the energy release rates for Mode I and Mode II, respectively. These values are used for the cohesive zone modeling of the interface. The validation of the model is reached by simulation of the DLJ tensile test.

2.1. Materials

The FiberForge RELAY® is an automated tape laying (ATL) facility that can produce flat preforms for consolidation out of endless fiber-reinforced thermoplastic tapes. The layup is stacked by ultrasonic welding points to keep the layup for further handling. With this ATL facility preforms were manufactured for the joining process. For the manufacturing of the test specimen a unidirectional CFRTP tape with polyamide 6 (PA6) matrix is used. The carbon fiber volume fraction of the CFRTP tape is 47 %.
The metal component is a high strength steel for automotive structures called HSLA340.

2.2. Joining process

The DLJ test specimens consist of two thermoplastic unidirectional laminates bonded to a steel sheet. To increase the joining strength two surface treatments are carried out on the steel surface. The joining process is carried out with a tooling that can be seen in Figure 1 where a sketch shows the right half of the tooling with the stacking in it. The tooling is heated up and the temperature of the upper and the lower CFRTP preform is measured with thermocouples. The heating is ongoing until the preforms reach a temperature of 270°C. The tooling is now transported into the heat press. The heat press builds up a pressure of 15 bar on the stacking. The heat press plates have a constant temperature of 80°C, hence the tooling with the stacking cools down. Now, the consolidation of the preforms to laminates is ongoing and at the same time the joining is realized. By reaching 100°C in the CFRTP laminates the press process is ended and the tooling can be opened.
The same joining process is used for manufacturing of the DCB and ENF specimens.

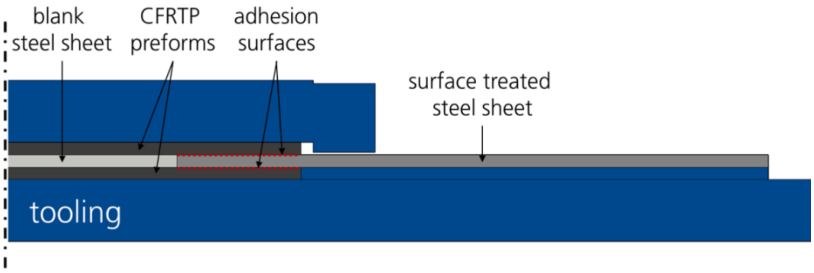

Figure 1. Detail of the symmetric cross section of the tooling with the stacking

2.3. Double lap joint tensile tests

Two surface treatments are investigated on the steel sheet. One is sandblasting (SB) with special fused alumina. The second surface treatment is coating of the blank steel sheet with the adhesion promoter Vestamelt® Hylink (VH) of Evonik Industries.
To investigate the influence of additional PA6 in the interface, a PA6 foil with a thickness of 0.2 mm or 0.4 mm is positioned in the interface before consolidation. Table 1 summarize the investigated configurations of surface treatments.

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Table 1. Configurations of surface treatment and additional PA6 foil

Sample name	Surface treatment	PA6 foil thickness [mm]
SB1	SB	0,2
SB2	SB	0,4
VH0	VH	-
VH1	VH	0,2
VH2	VH	0,4

Six specimens per configuration are tested based on the standard DIN EN 1465. The adhesion area is 25x25 mm². The DLJ geometry with dimensions can be seen in Figure 2.
All test specimens were conditioned before testing according to the standard DIN EN ISO 1110 to ensure the laminates reach the moisture content that would be obtained in standard atmosphere.

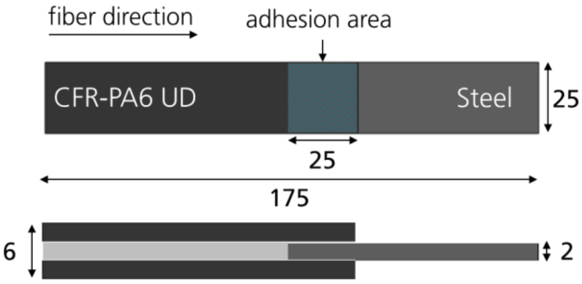

Figure 2. DLJ test specimen with dimensions [mm]

In Figure 3 the determined joint strength with standard deviation and the equivalent maximum force is summed up for all configurations. Overall the VH treatment is slightly better by taking higher joint strength in contrast to SB. The positive effect on the joint strength by the insertion of additional PA6 foil in the adhesion area could be determined. Up to 25% higher joint strength is achieved for the VH treated specimen with the insertion of PA6 foil.

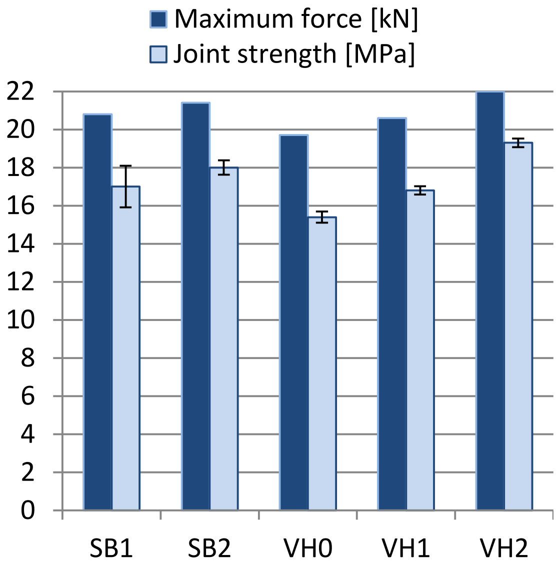

Figure 3. Maximum force and joint strength of all configurations

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2.4. Double cantilever beam and end notched flexure tests

The following test results are carried out for the surface treatment SB2. Based on the standard ASTM D 5528 the DCB tests are carried out. To ensure the same deflection of the dissimilar beam arms the following equation (Eq. 1) is used [3].

$$\frac{h_{CFRTP}}{h_{Steel}} = \sqrt{\frac{E_{Steel}}{E_{CFRTP}}} \tag{1}$$

The steel arm thickness is given by $\boldsymbol{h_{Steel}} = 2.0$ mm. According to that the calculated thickness of the CFRTP is $\boldsymbol{h_{CFRTP}} = 2.7$ mm. The DCB test setup is shown in Figure 4.

Figure 4. DCB test with specimen out of CFRTP laminate (top) and steel (bottom)

The ENF test is according to the standard AITM 1.0006. The ENF specimens are cut out of the tested DCB specimen with an initial crack length of 40 mm and a length of 115 mm. The test setup for the ENF testing can be seen in Figure 5. Here, the deflection of the beam is measured by a displacement transducer at the bottom of the beam.

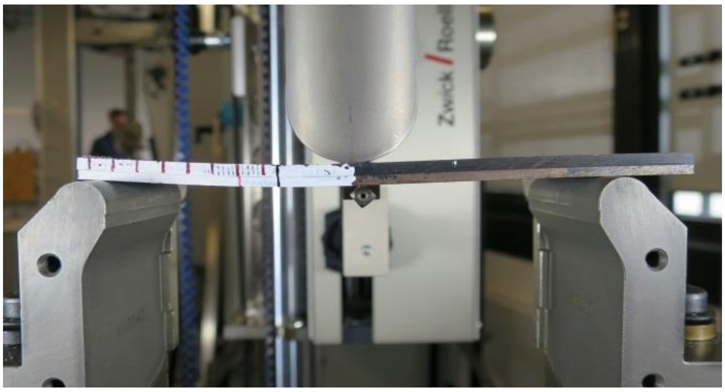

Figure 5. ENF test with specimen out of CFRTP laminate (top) and steel (bottom)

Out of the force-displacement curves and the delamination length of the DCB and ENF tests the energy release rates are determined according to the mentioned standards above. For the calculation of the energy release rate in Mode I three different methods are possible. These are the modified beam theory (MBT), compliance calibration method (CC) and the modified compliance calibration method (MCC), whereby the MBT method provides the most conservative value and will be used for the simulation. The results are summarized in Table 2.

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Table 2. Energy release rates G_{IC} and G_{IIC} determined through the DCB and ENF test results for the surface treatment SB2

	G_{IC} [J/m²]			G_{IIC} [J/m²]
	MBT	**CC**	**MCC**	
Mean	353	354	368	1451
Standard deviation	18%	19%	15%	17%

3. Modelling and simulation

To manufacture CFRTP-metal hybrid structures by the use of the direct adhesion joining technology and enable the design of such structures the modelling of the interface is necessary. Therefore the interface is modelled by cohesive surface in the commercial FE software Abaqus/explicit 6.14.

3.1. Numerical model and material models

The CFRTP component is modeled using continuum shell elements. The anisotropic material properties are considered by elastic properties with local orientation and as damage criterion Hashin´s failure criterion is used that is implemented in the FE software [4].

The steel HSLA 340 component is implemented with solid elements and elastic-plastic behavior. The plastic hardening is described by tabular input [5]. Damage occurs for the steel component when the ductile damage criterion with maximum plastic strain is fulfilled followed by a linear degradation.

The cohesive surfaces are modeled as a bilinear traction-separation law for the tensile (Mode I) and shear (Mode II) failure [4]. The corresponding energy release rates G_{IC} and G_{IIC} are used from the test results mentioned above. The stiffness K is assumed relating to the matrix stiffness of PA6. The strength values in normal and shear direction are calibrated by simulation of the DCB and ENF tests. The cohesive surface material model between the sandblasted steel and the CFRTP is summarized in Table 3.

Table 3. Cohesive surface material model for the interface between sandblasted steel and CFRTP

Energy rel. rate G_{IC} [N/mm]	**Energy rel. rate G_{IIC} [N/mm]**	**Stiffness K [N/mm³]**	**Normal strength s_n [MPa]**	**Shear strength s_s [MPa]**
0.353	1.451	1300	10	25

The simulation result of DCB and ENF tests is compared in the following Figure 6. The DCB experimental data show a high initial stiffness that is caused by the low deformation of the test specimen. The deformation is an effect of the joining process at high temperatures and the unsymmetrical arrangement of the beam arms. Afterwards the simulation and the experimental data are in good agreement in case of the maximum force at crack starting and the decreasing force at crack propagation. The ENF simulation reproduces the initial stiffness of the test results and the maximum force at crack starting within in the standard deviation.

It could be summarized, that the force-displacement curves of the simulation are in good agreement with the experimental data. The curves are located within the range of the test results. So this model is able to reproduce the interface failure and can be used for the DLJ test simulation.

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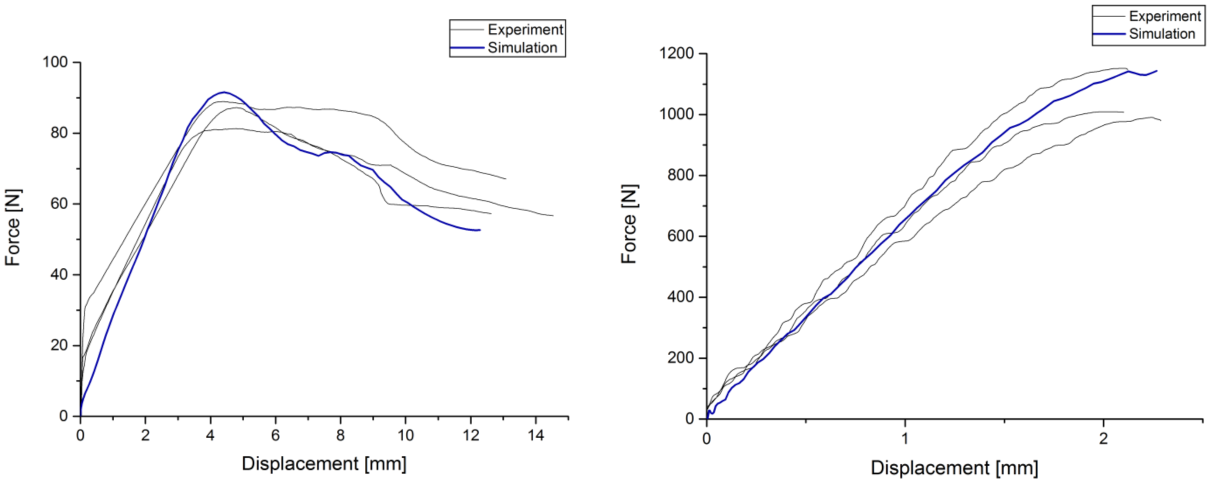

Figure 6. Comparison between the DCB (left) and ENF (right) test results with simulation

3.2. Validation of the model

The validation of the cohesive surface model is done by the simulation of the DLJ test for the surface treatment SB2. The FE modelling for the CFRTP and steel components is as described above. The FE model is pictured in Figure 7.

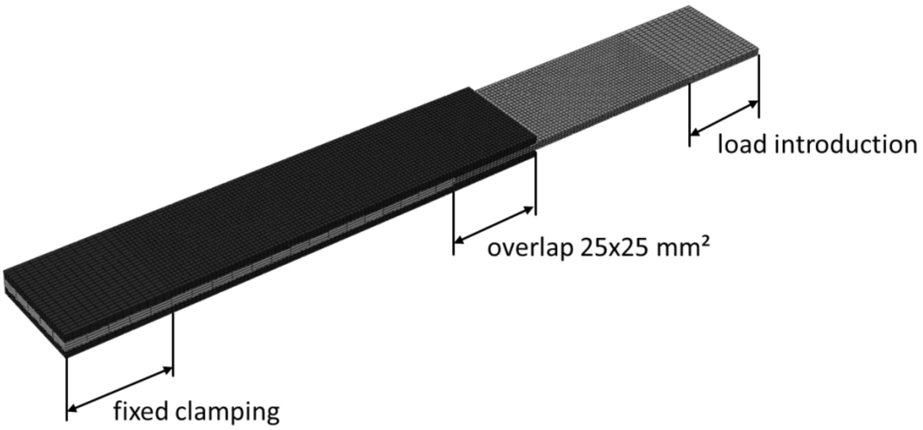

Figure 7. FE model of the DLJ specimen with CFRTP (black) and steel (grey)

The comparison between the experimental shear stress over displacement curves and the simulation are shown in Figure 8. In the simulation the stiffness of the joint is slightly higher as the experimental data. The plastic damage behavior of the joint after the first stress peak and also the maximum joint strength can be reproduced by the simulation. Overall the simulation is in good agreement with the experimental data.

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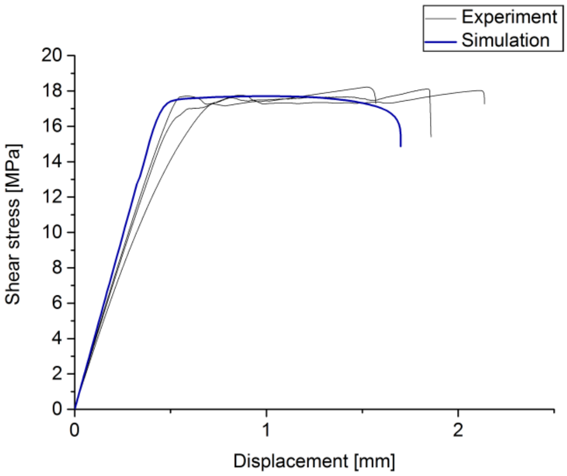

Figure 8. Comparison between the DLJ test results with simulation

4. Conclusions

The direct adhesion of CFRTP with metal is a joining technology that offers an automatable and reproducible process. Especially the consolidation and the joining process are realized in one step, thus subsequent processes like in adhesive bonding are not needed. Furthermore, in this work it is shown that high joint strength are achievable.

In the investigations CFRTP preforms made with the FiberForge RELAY® are combined with surface treated steel to consolidate the preforms and at the same time join with the steel sheet to DLJ specimens. Surface treatments were sandblasting and coating with the adhesive promoter Vestamelt® Hylink. The positive effect on the joint strength by the insertion of additional PA6 foil in the adhesion area could be determined. Up to 25% higher joint strength is achieved for the VH treated specimen with the insertion of PA6 foil.

To model the interface of the SB2 treatment DCB and ENF tests were conducted to determine the energy release rates in Mode I and Mode II, respectively. Afterwards a cohesive surface model is implemented in Abaqus/explicit 6.14. The simulation showed good agreement with the experimental data of the DCB and ENF force-displacement curves. The validation of the model is reached by the simulation of the DLJ test with SB2 treatment. Here, the simulation was able to reproduce the behaviour of the joint. Overall the model showed good agreement with the test results.

Further investigations are planned on the presented direct adhesion joining technology to use it in component level.

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