THE INFLUENCE OF INTERFACE SPECIFICATIONS ON IN- AND OUT-OF-PLANE LOADED HYBRID JOINTS

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ABSTRACT

Metal inserts are a common approach to establish connection points for carbon fibre reinforced polymer (CFRP) components. The classic design has drawbacks regarding weight and induces stress concentrations at the interface between insert and CFRP laminate due to stiffness discontinuities. In this paper a new biomimetic inspired geometry for inserts with three different interface specifications is presented. The additively manufactured titanium alloy Ti6Al4V part is realised in plain configuration, with lattice structure, and with lattice structure and pins, and is bonded to a CFRP laminate. Specimens for two different load cases – lap shear specimens for in-plane and peeling specimens for out-of-plane loading – are manufactured and tested on a hydraulic test rig. Beside the load and displacement measurements, additionally, the surface displacement of the out-of-plane loaded specimen is evaluated using three-dimensional digital image correlation.

For lap shear specimens predominantly shear and for peeling specimens predominantly normal stress is responsible for failure. The interface specification does not change the stiffness of the lap shear hybrid joint significantly. However, the total failure load changes considerably with lattice structure and pins yielding the highest strength. Similar observations regarding the total failure load are made at the peeling tests. Especially, the protruding pins lead to a damage tolerant hybrid joint. Compared to the other specifications, local damages at the pinned design only marginally influence the surface deformations in other areas.

1 INTRODUCTION

Lightweight design is concerned with the reduction of mass without neglecting safety aspects. A popular approach to reach this goal is the usage of high-performance materials with high stiffness- or strength-to-weight ratio [1, 2]. Therefore, different materials for different application areas and load cases are used in one assembly and need to be joined efficiently. Carbon fibre reinforced polymers (CFRPs) have these desirable properties, but, the connection to other components is challenging [3]. Classical solutions, so-called inserts, often do not fit lightweight expectations. Furthermore, the material properties of commonly used woven CFRP laminates and titanium alloys (as common materials for inserts) do not match well. Especially, the stiffness of titanium is much higher than the stiffness of woven CFRP fabrics. The resulting stress concentration at joints and interfaces between the two materials can be reduced by smooth transition areas [3]. For this reason and following a biomimetic approach, a comb shape geometry was designed for the Ti-parts [4]. Beside the stiffness aspect, also the interface area is increased. This study is concerned with hybrid joints with this advanced geometry and different optimised interface specifications for aeronautical applications. Focussing on two critical load cases for inserts, the geometry and the interface specifications are applied to specimens for in- and out-of-plane testing.

Typically, single lap adhesive joints are designed to predominantly carry shear loads in the bond layer [5]. Additive manufacturing (AM) creates further possibilities regarding the interface specification of the metal adherends, e.g. a defined surface roughness, realised as a rectangular lattice structure in this study, or protruding pins. The application of such pins in adhesive connections reportedly increases the load capacity of lap joints [6-8]. Similar observations were made for out-of-plane loaded hybrid joints with an advanced geometry and interface specification [9].

However, there is still a lack of comparative studies of the influence of different AM interfaces on adhesive joints in different load cases. This paper investigates hybrid joints for both load cases with three different interface specifications: plain, with lattice structure, and with lattice structure and pins.

2 MATERIALS AND METHODS

The specimens for in-plane tests are lap shear specimens and their geometry is based on the *ASTM D5868* standard (see Fig. 1, left). In total, 15 specimens are tested in in-plane direction, 5 of each interface specification (plain, lattice structure, lattice structure and pins).

The specimens for out-of-plane tests are called peeling specimens and the geometry of the biomimetic inspired roots have the same dimensions as for the lap shear specimens, but, are positioned circular symmetric to avoid predominant directions for stress concentrations (see Fig. 1, right). Two specimens per interface specification (plain, lattice structure, lattice structure and pins), i.e. 6 specimens in total, are tested in out-of-plane direction.

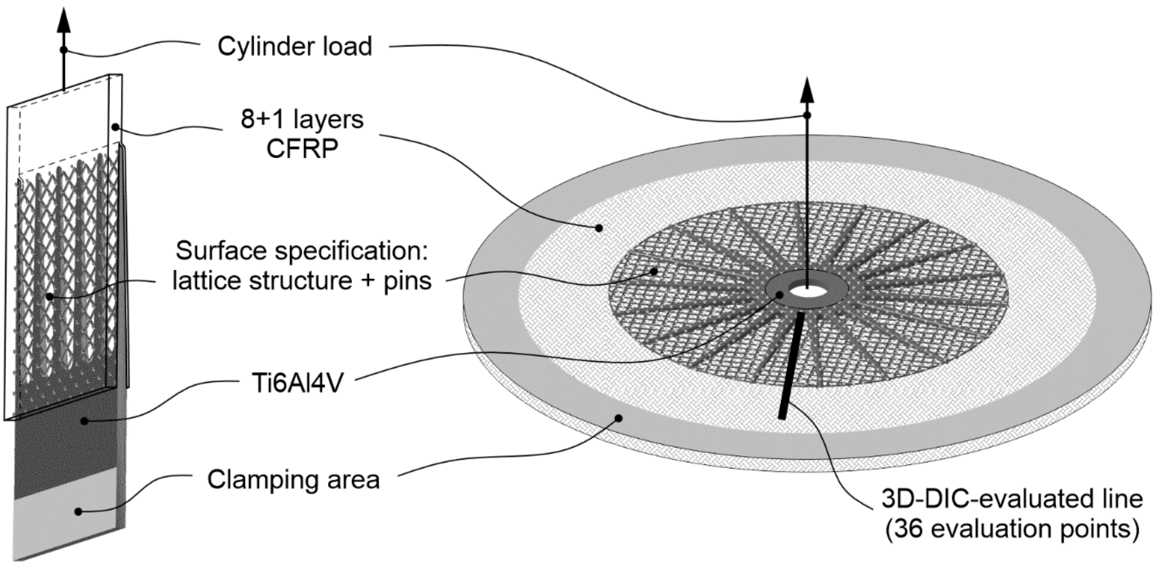

Figure 1: Left: Schematic of lap shear test specimen (Ti adherend: 80x25.4x1.5mm);
Right: Schematic of peeling test specimen (Ø140mm, Ti adherend: Ø80x1.5mm);
Root geometry: length 29mm, cross section tapered 2x1.5mm → 1x0.5mm;
Lattice structure geometry: spacing 2x2mm, cross section 0.3x0.3mm;
Pin geometry: height 0.5mm, cross section Ø0.3mm.

The metal parts are made of the AM titanium alloy Ti6Al4V with the specifications listed in Tab. 1. They are inlaid between the 8^{th} and 9^{th} CFRP prepreg layer (see Fig. 1) and are co-cured in an autoclave. The matrix material of the CFRP is used as adhesive between metal and composite adherend. Detailed specifications of the prepreg system *GG200T-DT01CN-42 (H 125cm)* from *Delta-Tech®* are represented in Tab. 1.

Carbon fibre reinforced polymer (CFRP)						
Yarn type	Reinforcement areal weight	Weaving style	Resin system	Resin content	Laminate thickness	Process
High-strength carbon	200 g/m^2	Twill 2x2	*DT01CN* (cyanate-ester)	42% by weight	0.23 mm	Autoclave

Titanium alloy		
Material	Process	Device
Ti6Al4V Grade 5	Direct metal laser melting 3D print	*EOS EOSINT® M 280*

Table 1: Material and manufacturing process properties.

All experiments are conducted with a displacement controlled hydraulic 25 kN cylinder by *Zwick/Roell®*. The cylinder force is measured with a *Zwick/Roell®* load cell. For the lap shear specimens, glass-fibre reinforced polymer tabs are adhesively bonded on both adherends to ensure in-plane loading of the hybrid joint. The specimens are clamped at these tabs with *MTS®* 647 Hydraulic Wedge Grips and are tested with a constant cylinder velocity of 0.5 mm/min.

The peeling specimens are clamped on a proprietarily developed circular symmetric clamping tool and the guided mandrel in the centre of the specimen follows a trajectory of 1 mm/min. Furthermore, the top surface of the peeling specimen is coated with a white primer and a black speckle pattern. This area is monitored during the test by two angular positioned 5 MP digital cameras with a sample rate of 2 Hz. The pictures are evaluated by the three-dimensional digital image correlation (3D-DIC) system *Correlated Solutions VIC-3D*. Especially, the coordinates of 36 points uniformly distributed on a line in radial direction (length approx. 36 mm, see Fig. 1, right) are analysed. All measured signals are post-processed and illustrated with *MATLAB®*.

In general, the in-plane tested lap shear specimens and the out-of-plane tested peeling specimens fail due to a superposition of different failure modes (e.g. shear and normal stress/peeling failure) in the adhesive layer of the hybrid joints. However, there is one predominant failure mode for both specimens. Lap shear specimens are designed to chiefly carry shear loads in the adhesive layer [5] and, therefore, the in-plane loads at these specimens induce predominant shear failure. The peeling specimen design is developed for predominant normal stress in the adhesive layer but the actual dominant failure mode needs to be validated.

3 RESULTS

3.1 Lap Shear Test

The mean value and the standard deviation of the cylinder load of all tested lap shear specimens with the same interface specification are illustrated in Fig. 2. The trends are depicted until the average total failure displacement of each specification.

The gradients of the trends, which represent the stiffness of the joints, do not vary or change significantly with different interface specifications. In dependence on the *ISO 6892-1:2016* standard, the stiffness is calculated by carrying out a linear regression with least square method between 10% and 40% of the damage initiation load of the plain configuration (see Eq. (1), with measured load F_i, calculated gradient k, measured displacement u_i, calculated load intercept c, and minimized error ε_i). The calculated gradient k of the linear function changes by 2% at most (see Eq. (3) and Tab. 2). Also, the coefficients of determination R^2 are greater than 0.9995 (see Eq. (2) and Tab. 2, with predicted load $\hat{F}_i$ and mean load $\bar{F}$) and, therefore, satisfy the requirements for a sufficient match between the straight regression lines and the measurement points.

However, the mean of the total failure loads $\overline{F_{max}}$ and the corresponding displacements $\overline{u_{max}}$ of the specimens change greatly with the interface specification, see Tab. 2.

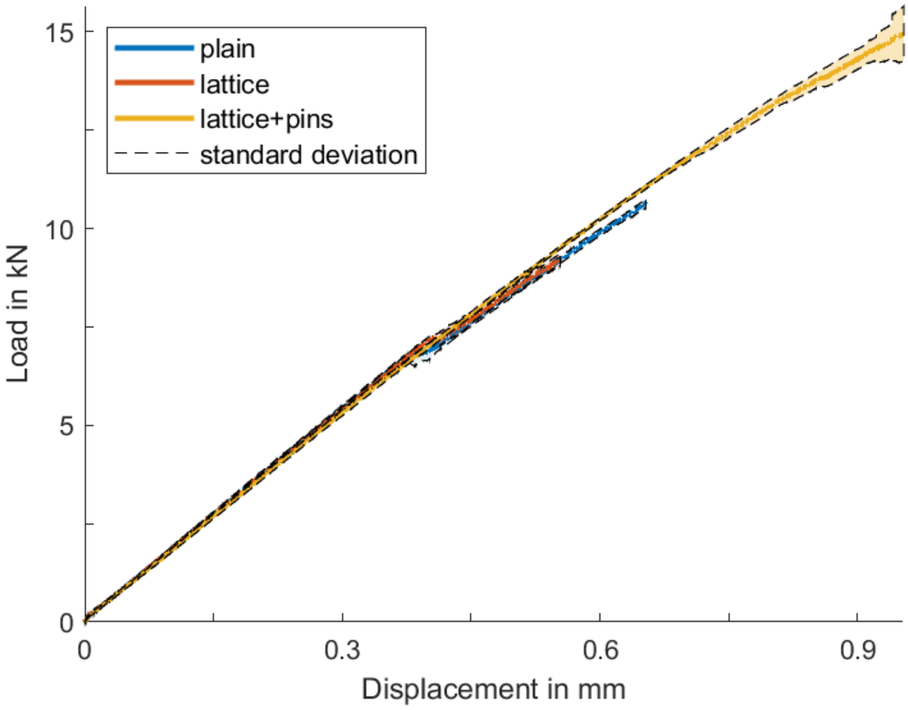

Figure 2: Load-displacement curves (mean value and standard deviation) of lap shear specimens with different interface specifications until total failure.

$$F_i = k\,u_i + c + \varepsilon_i \tag{1}$$

$$R^2 = 1 - \frac{\sum_{i=1}^{n}\left(F_i - \hat{F}_i\right)^2}{\sum_{i=1}^{n}(F_i - \bar{F})^2} > 0.9995 \tag{2}$$

$$\Delta k = \frac{k_{plain} - k}{k_{plain}} \times 100\% \tag{3}$$

	Plain	Lattice	Lattice + Pins
$\overline{F_{\max}}$ $[kN]$	10.65	9.14	14.94
$\overline{u_{max}}$ $[mm]$	0.65	0.56	0.95
k $[kN/mm]$	17.98	17.95	17.62
R^2 [1]	0.99996	0.99997	0.99994
Δk [%]	0	-0.18	-2.00

Table 2: Statistic parameters of lap shear tests (5 tests per interface specification).

3.2 Peeling Test

In Fig. 3 the load-displacement curves of one specimen per interface specification are shown. The trends of all specifications are similar and replicate a load-deformation curve of a membrane with the same boundary conditions, but, the total failure load of the specimen with lattice structure and pins is approximately by half greater than the total failure loads of both other interface specifications. The lattice structure without pins does not have a significant impact on the failure load of the joint.

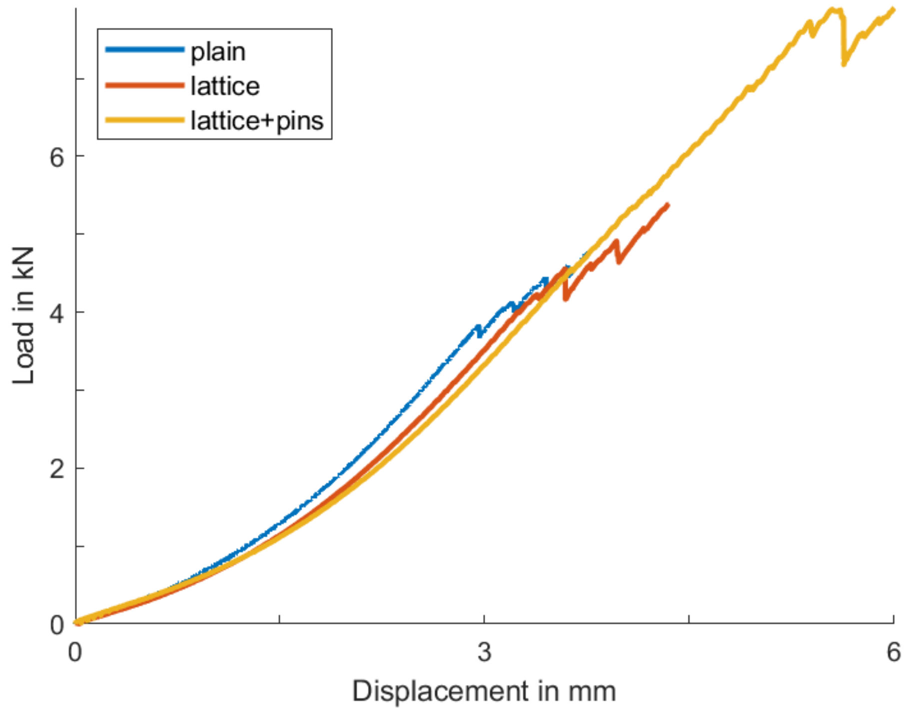

Figure 3: Load-displacement curves of peeling specimens with different interface specifications until total failure.

For a more detailed evaluation of the failure behaviour, the displacement of the surface along the radial line, depicted in Fig. 1, is considered. The displacement is transformed from the camera coordinate system into a static specimen-related coordinate system. For verification purposes the out-of-plane displacement is compared to the cylinder displacement measurements and shows good agreement.

The 3D-DIC-evaluated lines on the top surface of the peeling specimens do not deform significantly during loading. Before damage initiation, the surface normal rotates by less than 6° compared to the unloaded surface normal. According to the assumptions of the Kirchhoff-Love theory for thin plates [10], regarding a constant cross section normal to the mid-surface during deformation, and using trigonometric functions, more than 99.4% of the load are transformed into normal stress. Consequently, peeling is the dominant failure mode of the out-of-plane loaded hybrid joints.

Figure 4 shows the out-of-plane displacement of 8 points along the 3D-DIC-evaluated line over time. Discontinuities in the trends indicate damage occurring in the observed area. Especially, relative displacements (e.g. jumps, drops) of adjacent points suggest significant peeling incidents in form of debonding (between metal part and 8th or 9th CFRP layer) or delamination (between 8th and 9th CFRP layer). In accordance with Fig. 3 damage initiation of all specimens starts at a similar displacement level. In particular, the configuration with lattice structure and pins restricts the initial damage to a small area. Discontinuities of the displacement of a single point are not observed on other points along the line.

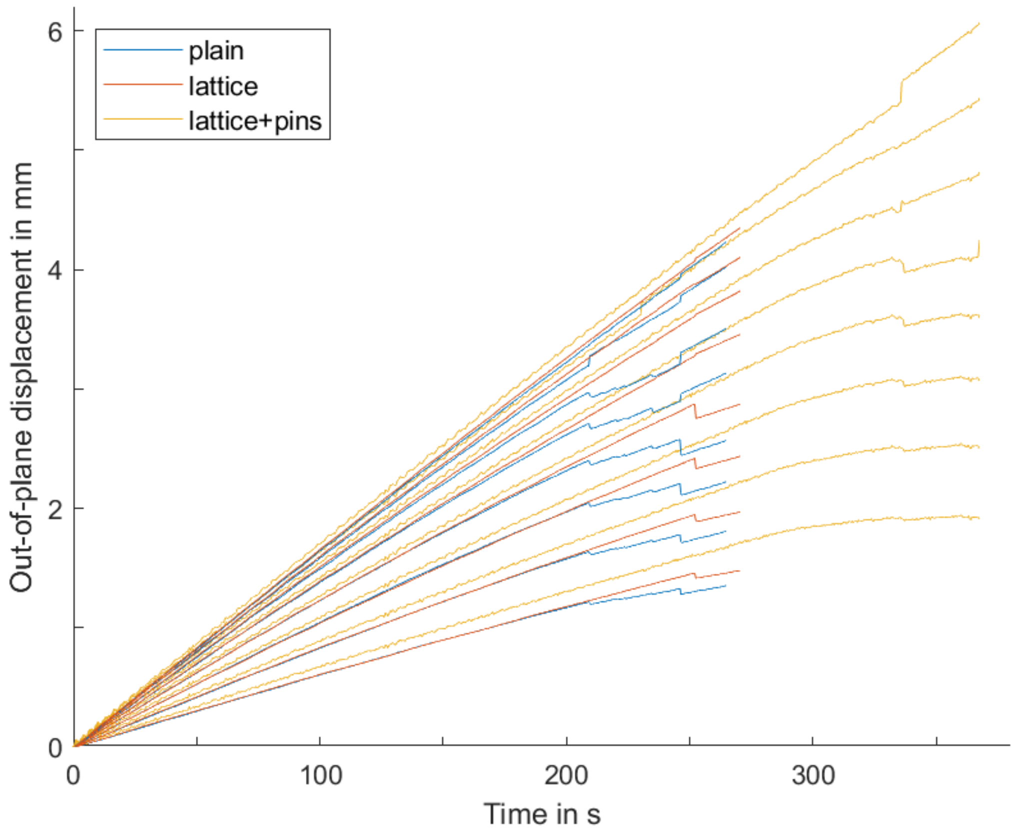

Figure 4: Out-of-plane displacement (evaluated by 3D-DIC, post-processed with *MATLAB*®) of 8 radial uniformly distributed points along a line on the top surfaces of the peeling specimens with different interface specifications until total failure.

4 DISCUSSION

The main purpose of this study is to evaluate the influence of an advanced geometry and different interface specifications at two different load cases and, therefore, with two different specimen designs. Although there is one dominant load case in the adhesive layer of each specimen before damage initiation, also other damage modes are active in the fracture process. At the lap shear specimens, the protruding pins are not sheared-off during total failure and, thus, need to be pulled out (peeling) or pulled through (fibres sheared by pins) the CFRP weave. Also, the predominant peeling failure at the out-of-plane loaded specimens is complemented by fibre failure of the CFRP top layer, especially during total failure of the joint.

In accordance with previous experiments with lap shear specimens of similar geometry and 12.7 mm width [4], the stiffness does not vary significantly with the interface specification. Moreover, the stiffness and total failure load scale linearly with the width of the specimen. Also, the findings of peeling tests regarding damage tolerance and concomitant higher total failure loads of out-of-plane loaded hybrid joints [9] are confirmed. The cited study [9] is based on surface strain evaluations, whereas, this research focuses on out-of-plane displacement measurements. However, to date not enough specimens in out-of-plane direction have been tested to assess the stiffness dependency on interface specifications.

Finally, the top surface of the peeling specimens is monitored by two cameras using the 3D-DIC method. Future experiments with lap shear specimens will be conducted with the same setup, to visually analyse and compare damage initiation and propagation for in- and out-of-plane loaded hybrid joints.

5 CONCLUSION

Classical metal attachment points for CFRP components, so-called inserts, have drawbacks regarding lightweight design aspects and stress concentrations. The developed geometries optimise the load transfer by reducing stiffness discontinuities. It has been shown in this contribution that the load bearing capacity in both, in- and out-of-plane load cases, can be increased approximately by half through the application of advanced interface specifications. However, the stiffness of the lap shear specimens is not influenced by the interface specification of the bond area, but, scales with the width of the joint.

Furthermore, this research demonstrates a method for out-of-plane loaded structure tests and improves the possibility to monitor peeling failure based on 3D-DIC and spatial out-of-plane displacement evaluation. Similar to real world applications, both test specifications (lap shear and peeling test) generate multiaxial stress states, but, causing one dominant failure mode. For the comparison of classical inserts and the advanced design, further studies will be conducted.

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