INFLUENCE OF AN OPTIMIZED 3D-REINFORCEMENT LAYOUT ON THE STRUCTURAL MECHANICS OF CO-BONDED CFRP JOINTS

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Keywords: CFRP, Z-Reinforcement, Joints/Joining, Damage tolerance

Abstract

Primary aircraft structures benefit from the weight savings potential of carbon fiber reinforced plastics (CFRP) which is strongly determined by the applied structural joint design. Through-thickness reinforcements address the issue of an efficient load transfer between adherents and an improved joint damage tolerance. The innovative technology in the present work encompasses a cost and time efficient manufacturing along with a beneficial contribution to mechanical joint properties. The impact of an advanced reinforcement design on structural mechanics is investigated through quasi static single-lap shear (SLS) tests. A correlation between an extended set of design parameters and load bearing capability, strain to failure and joint stiffness is discussed. Recommendations are given for the significant improvement of each of these properties and for dealing with the arising trade-off.

1 Introduction

Carbon-fiber reinforced plastics (CFRP) are increasingly used in primary aircraft structures due to their weight saving benefits gained by superior specific in-plane strength and load-conforming design [1]. Considering the anisotropic material behavior and laminar structure of CFRP, major challenges arise in the field of structural joint design. Their load carrying fiber structure and out-of-plane properties have to be considered [2]. Adhesive bonding of composite joints respects the fiber structure and curing of both CFRP and adhesive are integrated into one process. However, shortcomings like spontaneous joint failure, poor out-of-plane properties (resistance against peel stresses) and a lack of appropriate non-destructive testing (NDT) methods require the development of a joining technology that is more damage tolerant than pure bonding. Therefore, so-called 'chicken rivets' are usually used to create a secondary load path, which however interrupt the load carrying structure in the composite. The fibers are cut by drilling the laminate, its cross-section is reduced significantly and delamination may occur in the surrounding area [3].

A number of different z-reinforcement technologies have been developed with the goal of mechanically interlocking adhesively bonded CFRP adherents. Progress has been made on methods like Z-pinning [4][5], HYPER joints [6] and CMT welded pins [7] to name a few.

An innovative joining technique was designed to handle the trade-off between the weakening of the adherent's material and the abrupt failure of an adhesively bonded interface [8]. A low-thickness sheet of titanium or stainless steel with bent reinforcement elements in the z-direction is positioned between two CFRP adherents before or during the co-bonding process. These out-of-plane pins work as damage arresting features to the joint by creating a

secondary load path through a meso-scale mechanical interlocking. In this way, the fibers are not cut but only deflected and the overall bonding area is enlarged with the prepreg resin being connected to the pre-treated metal surface. Bending technology requires a rectangular pin cross section, in which the higher area moment of inertia is aligned with the loading direction. Pin shapes can be designed depending on the actual loading case, i.e. straight for shear stress conditions and with an arrowhead to retain out-of-plane or peel stress.
A rising volume share of reinforcements is expected to lead to a stronger lateral fiber distortion and thereby to a degradation of the composite’s in-plane properties without improving the structural mechanics to the same extent. In this work, an advanced sheet design is investigated varying a set of geometrical parameters on single lap shear specimens to find an optimal z-reinforcement-density and -array in the joint area on two different sheet thicknesses.

2 Manufacturing

The present approach allows integrating reinforcement elements into the co-bonding process of two CFRP laminates without any additional machining of adherents. Spiked metal inserts are introduced into a pre-impregnated laminate (prepreg) during its curing cycle. Insertion of these reinforcements into dry fabrics has also been successfully proved, but will not be further discussed in this publication.
Low thickness metal sheets of 0.2 and 0.4 mm are laser-cut to shape the pin geometry that is bent out-of-plane in a subsequent process step (see Figure 1). The respective tooling was developed by Hölzel Stanztechnik and will be further developed to allow the stamping of the metal foil instead of laser cutting in order to optimize the machining process and to consider future high-rate serial production of the inserts.

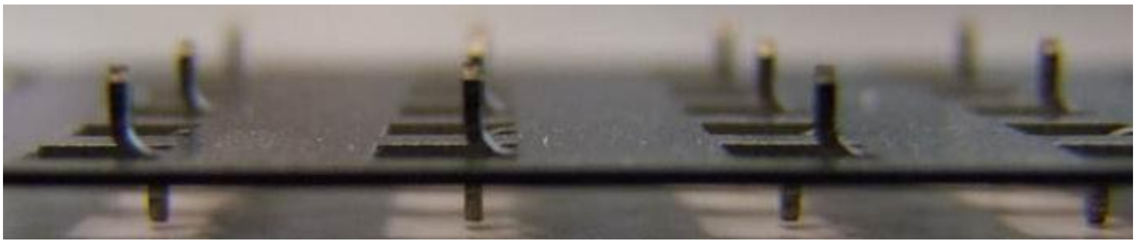


Figure 1. Detail of a metallic sheet with out of plane bent pins for the manufacturing of reinforced CFRP/CFRP single lap shear joints

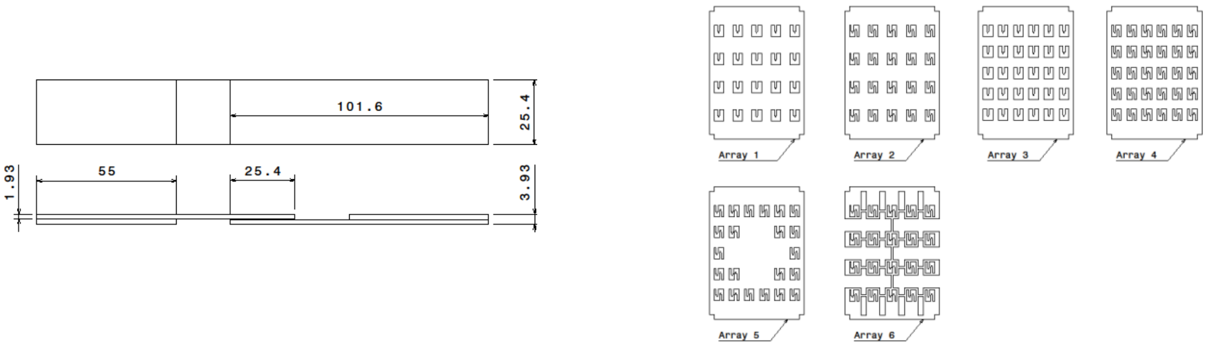
For the first curing step, the reinforcement sheet is positioned on the uncured laminate in an autoclave with elevated pressure and temperature so the metal spikes can penetrate the fiber/matrix system. Subsequently, the second, uncured adherent is placed on the reinforced area of the cured hybrid laminate and also set under pressure and temperature. A 3D-reinforced joint is manufactured using the curing steps of the co-bonding process, as explained in [8].

3 Experimental

3.1 Materials and Specimens

Specimen adherents were manufactured from HexPly® M21/198/T800S medium grade unidirectional prepreg, provided by the Hexcel Corporation. A quasi-isotropic layup $\{+45/-45/0/90/0\}_S$ was used to compose the laminates with a nominal thickness of 1.93 mm.
Stainless steel 1.4301 was used to produce the reinforcement sheets with six different types of pin layouts (Figure 2b), positioned in the 25.4 mm² overlap area of the single-lap shear joint

geometry (Figure 2a). The metallic sheets were sandblasted and plasma treated to increase the adhesion to the adherent on an enlarged, roughened and cleaned metal surface.



a) b)

Figure 2: a) SLS specimen geometry; b) Reinforcement sheet arrays investigated with 5x4 and 6x5 single and double pinned windows; arrays 5 and 6 are stress and flexibility optimized respectively

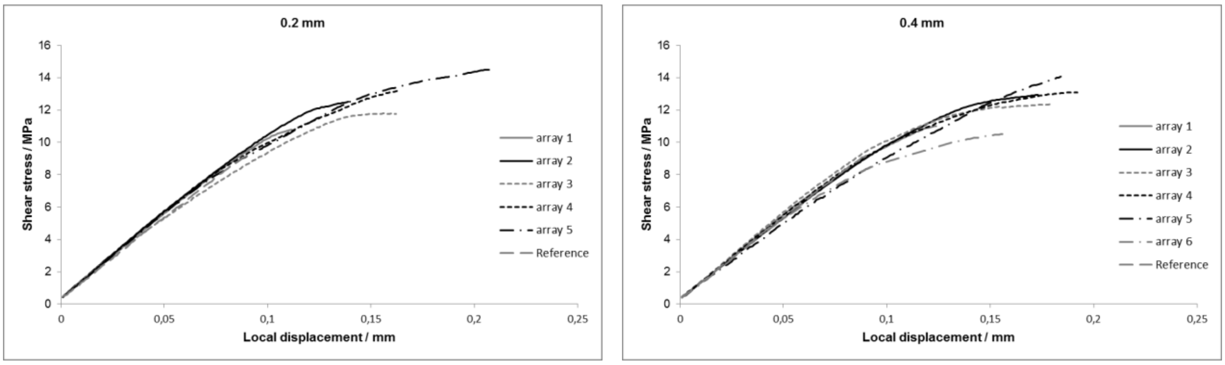
Basic arrays of 5x4 and 6x5 (array 1 and 3) were investigated and modified to derive information about the influence of a varying pin spacing (array 2 and 4), a stress optimized layout (array 5) and the design of the pin carrying sheet structure (array 6 , Figure 2b). Pin density is adjusted by the amount of windows that contain the reinforcing elements and its number per window, i.e. in the present study one or two pins per window. Since the sheet forming process does not allow a symmetric array of pins, an average pin density and pin spacing was calculated, respectively. Distance from the barycenter of the corner located windows to the lateral and to the longitudinal edges of the overlap area was chosen to be 2.5 and 1.5 mm respectively for reasons of geometric constraints. For unsupported single-lap shear test configurations, secondary bending causes peel stresses and thus stress concentrations in the lateral edges of the joint overlap area. Moreover, longitudinal elongation of the overlap area is zero in the center and increases towards the edges. Array 5 is expected to take account of the superposition of peel and sheer stresses, saving material in the area of low stress levels. Performance of arrays with pin rows only at the lateral overlap edges are planned to be published soon. Array 6 was designed to save material of the load bearing metal foil and also to investigate the influence of a more discontinuous interface between the CFRP adherents and reinforcement sheet. This structure is more flexible and expected to be useful in applications of a curvature/double curvature joint geometry, e.g. in the stringer run-out area of an aircraft’s fuselage. Sheet thicknesses of 0.2 and 0.4 mm were investigated and affect the rectangular pin cross-section, which is defined by 0.6 x 0.2 mm and 0.6 x 0.4 mm respectively. Pin height (bottom to top of the triangular head shape) depends on the bending radius. An in-plane pin height of 2.4 mm results in an out-of-plane height of approximately 1.73 mm with a bending radius of 0.4 which was found not to cause micro cracks in the area of plastic deformation at the root of the pin. FM® 300K epoxy film adhesive supplied by Cytec Industries was applied on both, reinforced and co-bonded baseline specimens.

3.2 Testing

Quasi-static, unsupported tensile tests were performed on a Zwick Z250 with a load range of up to 250 kN and a 0.5 % reaction force recording tolerance. Specimens were loaded displacement controlled with a crosshead velocity of 13 mm/min. The displacement at the overlap area was recorded using a 50 mm extensometer. All test runs were performed at an atmosphere of 23 °C and 37 % relative humidity. The presented micrograph images were taken with a Reichart-Jung Polyvar microscope.

4 Results

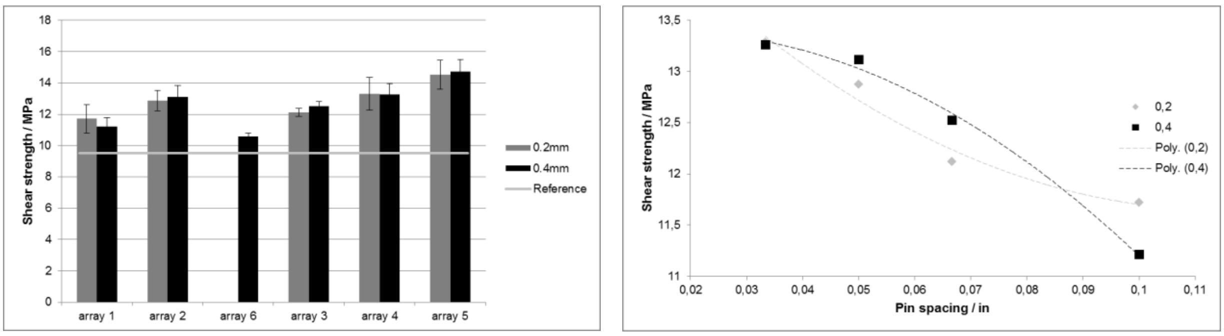
Figure 3 shows the load transfer characteristics for all configurations investigated. Mean shear stress is plotted versus local joint displacement.



a) b)

Figure 3: Mean shear stress plotted versus local displacement for 3D-reinforced CFRP joints with a) 0.2 and b) 0.4 mm sheet thicknesses

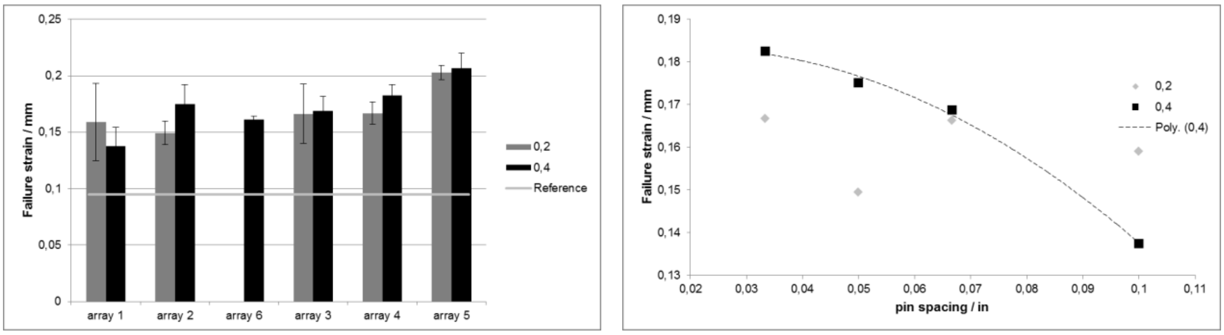
Shear stresses are calculated by dividing the load by the actual overlap area. The local joint displacement is the distance the extensometer recorded during testing. In the beginning of the testing sequence, shear stresses for both, baseline specimens and reinforced joints follow a linear slope. Depending on the pin layout on 0.2 mm sheets introduced into the joint, growth decreases slightly before (arrays 3, 4 and 5) or significantly after (arrays 1 and 2) the ultimate failure of the baseline configuration. Stages of steady slope for 0.4 mm sheets cover about the same local displacements after the linear stage of the reference joint. The insertion of arrays 5 and 6 lead to an overall lower joint stiffness and the latter one fails at significantly lower loads, compared to configurations 1-5. Unlike earlier investigations on reinforced CFRP joints [7][8], no distinct first failure event could be determined, because a rectangular corner geometry was chosen instead of a fillet configuration. However, discontinuities were observed in the non-linear section of the curves, in particular for arrays with 0.2 mm sheets, which are assumed to result from sheet deformation and crack propagation through the pin rows of the reinforced joint area. In this regard, a rising amount of pins per joint area seems to be detrimental to the joint stiffness, which needs to be considered in the following discussion of mechanical results.
Mean shear strength of all pin arrays investigated on sheets of 0.2 and 0.4 mm thickness is shown in Figure 4a).



a) b)

Figure 4: a) Mean shear strength of arrays showing a varying pin spacing and layout; b) correlation between shear strength and pin spacing of reinforced joints; from right to left: array 1, 2, 3 and 4

It can be clearly derived from Figure 3 and Figure 4 that the reinforcement arrays with a higher pin density lead to a higher shear strength. The increase of shear stress related to the co-bonded baseline configuration varies between 11 % (10.6 ± 0.2 MPa) and 55 % (14,7 ± 0.74 MPa) for arrays 1 (containing 20 pins) and 5 (with 60 pins on a 0.4 mm sheet), respectively. Even though array 4 (13.3 ± 0.7 MPa) contains less pins, their positioning in the overlap area following the same pattern as of array 5 (14.7 ± 0.7 MPa), the stress optimized layout, performs better in terms of shear strength. To get a more distinct understanding of the correlation between shear strength and pin spacing (i.e. density), a corresponding plot was created (Figure 4b) taking data of arrays 1, 2, 3 and 4 only, for reasons of comparability. The curves show different tendencies for 0.2 and 0.4 mm sheet thickness. For an increasing pin density, values for 0.2 mm grow further, whereas those for 0.4 mm sheets seem to approach a maximum level of shear strength. A higher pin density in the overlap will be investigated in order to get an estimation of how the curves would be extrapolated for a lower pin spacing than that considered in this work. This could also give evidence in to what extent scatter is determining the shape of the compensation curve.
Recalling the damage tolerance improvement as one of the main criteria to judge the joint performance, strain to failure is to be paid even more attention on in comparison to shear strength. Figure 5a) shows the respective values of mean strain to failure for all configurations investigated in comparison to the reference joint.



a) b)

Figure 5: a) Mean strain to failure of arrays showing a varying pin spacing and layout; b) correlation between strain to failure and pin spacing of reinforced joints; from right to left: array 1, 2, 3 and 4

The stress optimized array 5 on both sheet thicknesses lead to the most significant increase of failure strain of up to 118 % (0.21 ± 0.01 mm) compared to the co-bonded reference joint (0.09 ± 0 mm). Contrary to the values for the joint shear strength in Figure 4, performance gaps between the single and double pinned windows are not existent for 0.2 mm sheet configurations (array 1 versus array 2) or vice versa (array 3 versus array 4) regarding failure strain. Array 3 (0.17 ± 0.03 mm; 30 pins) exceeds the strain values for array 2 (0.15 ± 0.01 mm; 40 pins), even containing 10 pins less in the overlap area. Since this is not the case for the 0.4 mm configurations, it is probable that reinforcement sheets with a low thickness lead to a considerable scatter due to plastic deformation of the pin during manufacturing processes. Basically, with regard to the failure strain for the array 5 reinforced joint design (44 pins), it can be derived that an optimized pin positioning is more important than the quantity of pins introduced into the joint area. Further investigations are still needed to infer on how the incontinuous pin layout in the overlap area affects the joint stiffness.
Characteristic fracture surfaces of all joints with reinforcement sheet thicknesses of 0.2 and 0.4 mm are shown in Figure 6. Regardless of the pin number and layout on 0.2 mm sheets, no pin was sheared off in arrays 1, 3, 4 and 5, but instead pulled out during testing, with cracks propagating through the first or both 45° plies which was already observed before [8].

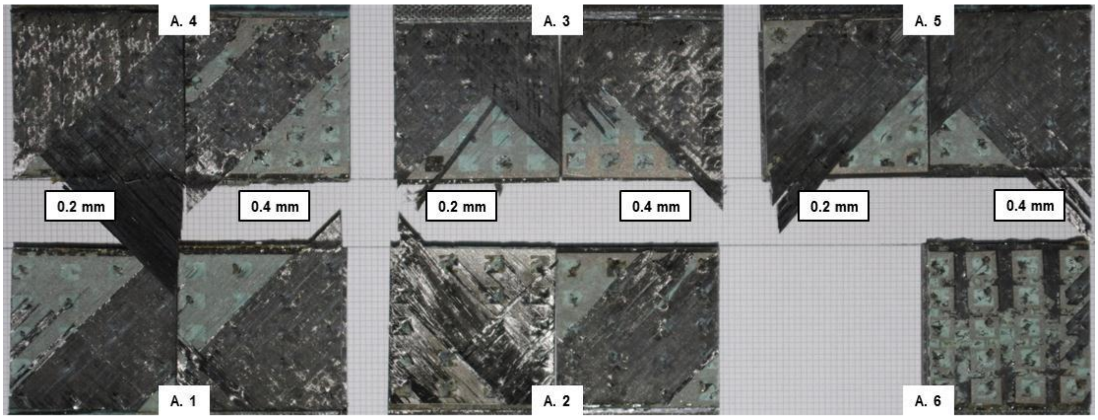
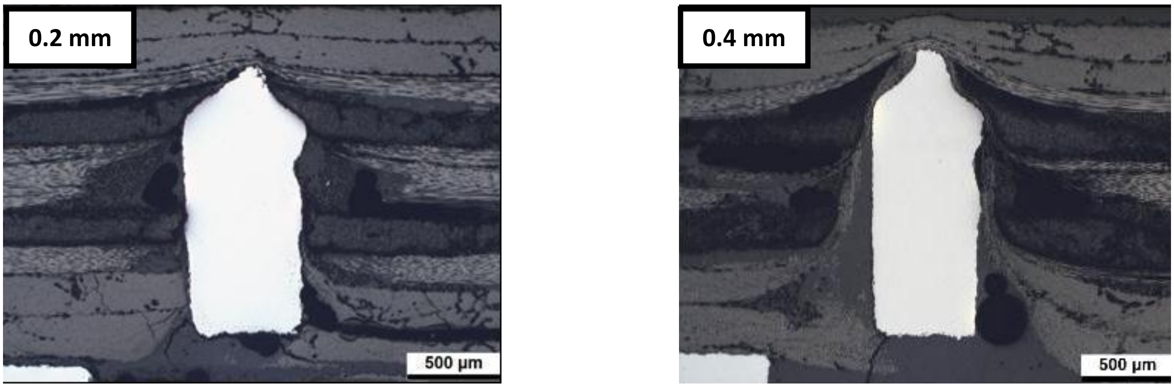


Figure 6: Fracture surfaces of all reinforcement arrays; cohesive failure at crack initiation and subsequent inter/intralaminar failure is clearly visible for configurations 1, 3, 4 and 5

Joints are expected to stand a higher level of deformation energy if pins could absorb more energy by an increased extent of plastic deformation, i.e. pin shear off. In future work, an optimized technology for the metal sheet surface pre-treatment will be applied to address this issue by improving the bonding quality of the CFRP/metal interfaces. Moreover, a mechanical interlocking on macro scale in the pin head area was stated to be an appropriate mean [7]. Secondly, crack initiation is dictated by and located in the area of high peel stresses at the edges of the overlap area, where the adhesive fails cohesively. Compared to the epoxy adhesive, the epoxy resin of the prepreg is less ductile and promotes the crack to propagate through the 45° plies decreasing the stiffness of the reinforced joints. It decreases with the amount of stress applied, which reflects the degradation of the laminates' toughness – in the later stages of the stress-strain curves (Figure 3) – the more the intralaminar damage propagates.
Also, pin surrounding plies serve as a supporting structure which raises the resistance of the pins against bending. This effect superposes with the correlation between individual plastic pin deformation and pin density at a given stress level. Fracture surfaces show a decreasing bending angle of the pins for an increasing amount of plies surrounding them, i.e. pin density. An optimized head shape is assumed to be an appropriate mean to mechanically interlock the pins with the laminate, increase the pins' plastic deformation and thereby absorb more energy during joint loading. The specimens reinforced with a pin layout following array 2 display an intralaminar failure which needs to be further investigated. The crack propagates from the adhesive bonded interface through the reinforcement sheet after initiation and causes fibers to detach from the surrounding resin.
It is assumed that after a first crack initiation and propagation, a second crack front initiates at the opposite overlap edge and causes the 0.2 mm sheets to elastically and plastically bend in an s-like shape. In this way local ratios of shear to normal stresses deviate from those of 0.4 mm reinforced joints, where no such sheet bending was observed. Intralaminar crack growth is not correlated to the amount of pins in the joint area like it seems to be for the thinner sheets, as can be drawn from the fracture surfaces of arrays 1 – 4 in Figure 6. Thus, increasing normal stresses are expected to promote intralaminar crack growth, which has to be proven by further investigations with optical strain mapping. However, like observed in earlier investigations [8], an increasing reinforcement thickness leads to a slightly decreasing intrinsic joint stiffness which indicates a higher level of energy absorbed by plastic deformation of pins before pull-out. A higher bending moment due to a 0.2 mm shifted load introduction might also affect the stress-strain curve (Figure 3). Similar to the joints reinforced with 0.2 mm sheets, joint stiffness is decreasing with the amount of load applied due to a decreasing overlap area (i.e. area moment of inertia) as the cracks propagate between

laminates. As mentioned above, array 6 shows the worst performance of all reinforced joints which is due to an extensive amount of pores and resin rich zones in the reinforcement sheet layer. Cracks initiate at the more discontinuous designed load carrying structure and propagate through the above mentioned defects. For an 0.2 mm sheet thickness, the stress optimized layout could not be realized.
A micrograph of a lateral cross-section of array 4 reinforced joints with 0.2 and 0.4 mm sheet thicknesses, approximately 10 mm from the edge of the overlap area is shown in Figure 7.



a) b)

Figure 7: Micrograph of a) 0.2 mm and b) 0.4 mm thickness pins after final joint failure; resin agglomerations and pores at the foot of the pin's bending radius are visible

A considerable amount of resin agglomerations and pores under the pin root (the bending radius) is observed on the very left bottom of metallic inserts. Cracks in the same area indicate the elastic lateral bending of the pin along the loading direction applied, caused by the resulting shear stresses. Fiber misalignment, resin nests, pores and cracks (pin head) are discontinuities that lead to a decreased shear strength and elongation to failure of the joint. This can be concluded from a comparison of the respective values for arrays 4 and 5 (see Figure 4a and Figure 5a). Shear stresses are lowest in the center area of the joint and thus pins could be detrimental to the laminates' in plane properties and to the CFRP/metal interface. Joint properties are not improved to the same extent by positioning reinforcement elements in the center of the overlap area. As expected, the number and scale of defects is higher for 0.4 mm reinforcements (Figure 7b), further reducing joint stiffness compared to the thinner reinforcements [4]. On the other hand, thinner pins underlie stronger deformations during both curing cycles in plastic deformation on compression and on bending, indicated by the smaller pin height in Figure 7. Since the pattern of deformation is not equal for all specimens of a series, a considerable scatter of shear strength, even more of failure strain, is noticeable for the static test results compared to 0.4 mm thickness pins (Figure 4 and Figure 5).

5 Conclusion and Outlook

In the present work it was shown that with the aid of an improved manufacturing process, 3D-reinforcements for CFRP/CFRP joint applications can be produced (cost and time efficiently) by the subsequent combination of stamping and bending of metal foils.
The implementation of these metallic reinforcements into the joint leads to significant increases in shear strength and maximum elongation endured during quasi-static single-lap shear testing. An increasing pin density and sheet thickness in the joint area leads to an increase in shear strength and failure strain compared to a co-bonded baseline joint. When the pin array is optimized towards the stress conditions applied to the joint, shear strength is further increased and elongation to failure improves up to 118 %. Less resin concentrations

and fiber ondulations are assumed to result in a better adhesion of the laminate to the reinforcement metal foil in the unpinned center of the overlap. It has to be taken into account that the increase of sheet thickness as well as pin density were observed to be detrimental for the joint stiffness. This is caused by an increase of energy absorption by plastic pin deformation and inter/intralaminar crack propagation in the joint area, respectively.

Future work will focus on an increased pin density at the edges of the overlap area of single-lap shear joints to improve through thickness strength. These investigations will be also supported by an optimized head shape design of the pins to achieve a macro mechanical interlocking with the laminate. Different methods of surface pre-treatment for both CFRP and metal will be tested in order to investigate possible optimizations of the joint's performance. An evaluation will be performed under static and fatigue loads and under varying environmental conditions. Furthermore, energy based tests will be done to determine the fracture toughness of reinforced CFRP joints on double cantilever beam (DCB) and end notched flexure (ENF) specimens.

6 Acknowledgements

We would like to thank our colleagues at Airbus Operations GmbH for their continuous support and commitment to our research activities on 3D-reinforced CFRP. We also want to express our appreciation to the Federal Ministry of Education and Research, Germany, (BMBF) for funding this research within the TransHybrid project.

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