1 Introduction

Carbon fiber reinforced polymers (CFRP) are nowadays applied to a number of primary structures and have gained in importance in the transportation industry in recent years. Due to their high stiffness to weight and strength to weight ratio they are considered to be an alternative to conventional structural materials with higher density in many areas. Along with a growing use of CFRP comes a growing demand for joining technologies that rise up to the challenges such a material poses. Special care has to be taken of fiber alignment and out of plane stresses because of the anisotropic behavior of CFRP and its laminar structure [1, 2]. Conventional bonding technologies such as adhesive bonding, bolting and riveting only partly meet these challenges. Bolting and riveting for example have a mandatory need for drilling the CFRP and therefore cutting continuous fibers in the CFRP which are essential for the load transfer [3, 4]. Moreover, the cross-section gets reduced, stress concentrations can appear around the holes and there is an imminent danger of delamination with drilling of fiber reinforced polymers [4–7]. Adhesive bonding on the other hand does not account for out of plane or peel stresses, it possesses low bonding strength and makes wide connection areas necessary [8].

Various 3D reinforcement methods have been studied over the recent years with the goal to establish either a mechanical link between the different plies of the laminate (structural reinforcement), or between two adhesive-bonded laminates (joining reinforcement) [9]. Tufting [10, 11], stitching [12–16] and z-pinning [10, 17–19] are examples of such reinforcement methods.

A novel joining technology now aims at combining the joining mechanisms form-fit and adhesive bonding, with an integrative joint approach [20, 21]. Arrays of vertical elevations (pins) are disposed on thin metal sheets through the modified cold metal transfer welding process (CMT-pin) of FRONIUS International [22]. The underlying CMT process is a low-energy arc-welding process which allows the energy efficient welding of thin metal sheets in a material gentle manner. The adjustment of the welding control, welding current, voltage, and the wire movement are key issues for the modified CMT-pin process. It consists of the following steps:

1. **Warm up and filler wire deposit phase**
   The filler wire is moved towards the weld-pool until a short cut ignites an electric arc between filler wire and metal sheet. The electric arc melts the metal surface and the filler wire. The end of the molten wire is moving down to the metal and dipped into the weld-pool on the surface.

2. **Cooling phase**
   Energy input is stopped. The molten weld-pool and attached filler-wire cool down.

3. **Pin sculpturing phase**
   Shaping of the welding agent is carried out through introduction of a combination of electric current and tensile force. This leads to tearing off the wire at a certain height with a specific pin geometry.

Possible pin shapes are cylinder pins with a flat ending, spike pins with a tipped ending, and ballhead pins with a spherical ending [21]. The combination of a ballhead pin with a small spike pin on top of it results in a ballhead spike pin. The ballhead with its spherical undercut supports the load transfer. The tipped ending on top enhances the draping of dry or pre-impregnated fibers onto arrays of such pins.

When fiber-textiles are placed onto arrays of pins, the pins penetrate the single layers. They push aside the fibers and build up a loose form with only little
influences to the fibers. After the curing process the pins form a through thickness reinforcement with the composite [21, 23]. This work determines the influence of this novel CFRP to CFRP joining technology on the load transfer behavior and damage tolerance. The focus is put on single lap shear CFRP to CFRP specimens (SLS) which are reinforced with thin metal inserts with arrays of pins (see Fig. 2) on top and bottom side. The metal inserts are located in the 30 mm overlap region between the two 110 mm long CFRP laps.

2 Experimental

2.1 Materials and specimens

The materials used for the specimens, in this study, were an epoxy resin from Hexcel Composites (Hexflow® RTM6) reinforced with high tenacity, standard modulus fibers from Toho Tenax for the CFRP parts. Metal inserts were made of stainless steel type AISI 304 with a sheet thickness of \( t = 0.6 \) mm. Ballhead spike pins were made of filler wire type AISI 316L. The SLS specimens were reinforced with pinned metal inserts and three different arrangements of 4 x 6 ballhead spike pins (Fig. 2). In the case of array 1 the pins had an equal distance arrangement (Fig. 2a). The outer two, across aligned columns of 2x6 pins were 1.5 mm away from the free edges of the metal insert. The inner two columns of 2x6 pins were \( p_x = 7.0 \) mm away from the outer two columns. The axial aligned 6 rows of pins had an equal pitch of \( p_x = 4.17 \) mm. In the case of array 2 (Fig. 2b) the pins were arranged at the end positions of the inserts. The outer two columns of 2x6 pins were 1.5 mm away from the edges of the metal insert. The inner two columns of 2x6 pins were \( p_x = 3.0 \) mm away from the outer two columns. In the case of array 3 (Fig. 2c) pins were arranged at the four corners of the insert in a triangular shape. The position of the first pin is equal to pin array 1 and 2. The pins had an equal pitch of \( p_x = p_y = 3.0 \) mm. The pin arrays were manufactured in an automated, computer controlled welding machinery. The welding head of the CMT unit was attached to a three axes moving portal, see Fig. 3. Blank metal inserts were fixated in so called “mounting plates” which were attached to the machine frame. The mounting plates were used for accurate positioning of the blank metal inserts for CMT-pin welding. The x- and y-axes were the in-plane movement directions of the CMT welding head, the z-axis was needed for lifting and lowering the CMT welding head away and towards the metal insert. The welding accuracy of the whole setup accounted to \( \pm 0.1 \) mm.

![Fig. 1. SLS specimen geometry, (a) Sectional view of the specimen, (b) Final SLS joint specimen.](image)

![Fig. 2. Three types of pin arrays on metal inserts: (a) array 1, (b) array 2, (c) array 3.](image)

![Fig. 3. Fully automated, computer controlled CMT welding machine used for the production of metal inserts with different arrays of pins.](image)
Fig. 4 shows a metal insert with pin array type 1 after being produced in the above mentioned automated pin welding process and before cleaning and sandblasting. The pins had a shaft diameter of 0.8 mm and an overall height of 3.3 mm. Prior to the draping process the thin metal sheets and pins were surface treated by cleaning and sandblasting in order to remove contaminations such as grease and welding tinder. At the same time sandblasting increased the roughness of the metallic surface and therefore increased the adhesion between the metal and the epoxy resin. This was proofed by fracture mechanical measurements which will be published elsewhere. In a final step the inserts were cleaned with an organic solvent.

For the preforming process the metal sheets were accurately and reproducibly fixed within a metal mould. A set of dry CFRP textile layers was draped onto the pin arrays (Fig. 5) in a symmetrical manner so that a quasi-isotropic lay-up was achieved.

CFRP specimen-panels (Fig. 6) were produced via a liquid resin infusion (LRI) process. This low pressure injection process has been chosen as a cost effective alternative to an autoclave process or a press forming process. Another reason for using LRI was the need for the application of dry fiber textiles due to their lower resistance against penetration of single layers by pins and the lower risk of wrinkles within the layers due to draping of the textile over the pins.

Single SLS-specimens were cut out of the final CFRP specimen-panels (Fig. 6) by waterjet cutting. Before waterjet cutting GFRP tabs were bonded onto the endings of the CFRP specimen-panels to ensure both a symmetric clamping of the SLS joint specimens within the test system and an axially aligned joining interface (see Fig. 1). The final joint specimens had a width of 25 mm and an adhesive bonding area of 750 mm².
Adhesive-bonded reference specimens were of identical shape. They did not contain metal inserts and were manufactured in a different way. Two separate CFRP panels with a quasi-isotropic CFRP stacking were bonded with 3M Scotch-Weld adhesive film type AF 163-2L.

2.2 Test methods

Tensile tests on SLS specimens were executed on a servo-hydraulic test system, MTS 322, with a load range of 250 kN. The specimens were loaded with a displacement controlled static loading at a crosshead velocity of 2 mm/min. The optical deformation measurement system ‘Aramis’ was used in order to get full field strain information of the specimens’ edges. One edge of the overlap region was therefore sprayed with graphite to form a speckle pattern on the surface. The relative movement of the single speckle pattern points was tracked by two cameras and computed into a three-dimensional displacement and strain field. This gave information about highly strained and hence highly loaded joint areas. Crack initiation and crack growth along the metal to composite interfaces in the hybrid joint could thereby be visualized in the post-processing. All tests were carried out at a laboratory atmosphere of 23 ± 1 °C, room temperature, and 50 ± 10 % relative humidity. All presented micrographs were taken with an optical stereo microscope type Olympus SZX12.

3 Results

3.1 Pin reinforced SLS joints

Fig. 7 shows the load transfer behavior of the SLS specimens reinforced with the three types of pin arrays as depicted in Fig. 2. Shear stresses are plotted versus local joint strains. Shear stresses were calculated by relating the measured load to the joining area of each specimen. Axial local joint strains were measured with Aramis at ± 10 mm from the overlap region (50 mm gage length).

Regardless of the pin array in use, at start the curves rise linearly until a first distinct load peak is reached, the so called “first failure stress” (FFS). This is followed by a load drop, and by a second load peak - load drop combination. This is then followed by a non-linear loading behavior until another maximum, the shear strength (SS), is reached. This occurs at high local joint strains between 2.5 - 4.0 %. After reaching the shear strength the loads drop and the specimens fail. The comparison of measured first failure stresses, shear strengths and derived total deformation energies is given in section 3.3.

![Fig. 7. Mean shear stress versus local joint strain for tensile tested pin reinforced SLS specimens.](image)

Fig. 8 shows the failed joint section of a SLS joint which was reinforced with pin array type 1. The first row of pins (left) were pulled out of the CFRP whereas three of rows pins (right) were sheared off with small metal residua left on the top surface of the metal insert. The metal insert still upholds the connection to the bottom CFRP. However, it is not visible to which extent the pins on the bottom insert surface were deformed. It is assumed, that elevated peel stresses at the edges of the SLS specimen occurred due to the change in cross-sectional area and therefore tensile stiffness. This may have lead to pull out of one row of pins. Possible influences of processing on the failure behavior have yet to be investigated.

The correlation between the load transfer graphs of Fig. 7 and post-processed Aramis data allows for a better interpretation of the stress strain curves and the failure processes within the SLS joints under loading.

The adhesive bonding line between the CFRPs and the metal insert faced the highest strains at first failure stresses (Fig. 9a). In these areas, crack
initiation and crack growth appeared predominantly. After further loading and complete failure of the adhesive bonding interface, the pins bear the applied load mainly due to the form-fit connection between the CFRP and the spherical undercut of the metal ballhead pins. At this stage of the test the area surrounding the pins faced the highest strains (Fig. 9b).

![Figure 8](image1.png)  
**Fig. 8.** Photograph of specimen, reinforced with pin array type 1, after final failure. Most of the pins were sheared off. One row of pins at the edge of the specimen was pulled out.

![Figure 9](image2.png)  
**Fig. 9.** (a) Distribution of major (axial/total) strains at first failure stress (FFS). (b) Distribution of major (axial/total) strains at pull out of the pins before reaching the shear strength (SS).

![Figure 10](image3.png)  
**Fig. 10.** Micrograph of pins after final failure. Carbon fibers below the pin heads are held back by the pins' undercut face.

![Figure 11](image4.png)  
**Fig. 11.** Micrograph of failed pins after final failure. The heads were sheared off and one layer of CFRP was held back and separated from the rest of the beam.

### 3.2 Adhesive bonded reference joints

The loading behavior of adhesive-bonded reference specimens can be seen in Fig. 12. The mean shear strength results to $7.9 \pm 1.8$ MPa at local joint strains of $0.21 \pm 0.05\%$. After reaching one distinct peak spontaneous failure sets in. Final joint failure is reached at strains of around $0.75\%$. These are much lower compared to strains of $> 4\%$ for SLS specimens with pin reinforcement.

Fig. 13 shows the failure behavior of an adhesive bonded specimen recorded with Aramis. Cracks initiate at the edges of the overlap region when maximum stresses are reached (see Fig. 13a).
The improvement is related to the reinforcing pins and their positions. The alignment of pins close to the outer ends of the overlap region of the SLS specimen reinforces the metal to CFRP interface. This is in the area where the highest peel stresses occur due to the abrupt change in cross-sectional area and the tensile stiffness. Also, crack initiation and propagation is delayed. In the case of pin array type 2 more pins (2 x 6) are closer to the outer ends compared to pin array 1 (1 x 6). Therefore, pin array 2 reaches higher first failure stresses.

Fig. 15 shows the comparison of the shear strengths of the three pin reinforced SLS joints with shear strengths of adhesive bonded reference joints. Similar to first failure stresses, the shear strength improves remarkably through the use of pins as reinforcement. Pin array type 1 reaches shear strengths of 15.5 ± 0.3 MPa. This shows + 5.5 % increase and + 16.7 % compared to pin array type 2 and pin array type 3, respectively. The comparison with adhesive bonded reference joints shows increased shear strengths of + 97.2 %, + 86.8 %, and + 68.9 % for the three SLS pin reinforced joint, respectively. In contrast to first failure stresses, the shear strength for pin array 1 is slightly higher than for pin array 2.
The amount of sheared off pins was counted and related to the overall applied number of pins for each batch of pin-reinforced SLS joint. This allowed for the correlation between the pin arrangement and the resulting failure stresses. In the case of joints with pin array 1, 77 ± 13 % of the pins were sheared off whereas 51 ± 19 % of pins were sheared off in the case of pin array 2. In the case of pin array 3 most of the pins were pulled out of the CFRP. Only 17 ± 19 % of pins were sheared off.

A direct relationship between the amounts of sheared off pins and the shear strength level can be concluded. The more pins are sheared off, the higher the shear strength of the pin reinforced SLS joints. Thus the form-fit of the pins needs to be improved in order to further raise the amount of pins that are sheared off and to fully exploit the maximum shear strength of pin reinforced SLS joints. This especially accounts for pins in areas affected by peel stresses.

Fig. 16 shows a comparison of the total deformation energy sustained by the four tested SLS specimen versions. The total deformation energy is defined as the area under the force vs. local displacement curve until the specimen is fully unloaded. Adhesive bonded specimens failed in a brittle and spontaneous manner at low loads and low local joint expansions (see Fig. 12). Therefore, the total sustained deformation energy results to 1.2 ± 0.4 kJ. In contrast, SLS specimens with pins were able to carry loads at a higher level until final failure at high local joint strains was reached (see Fig. 7).

The three SLS joint versions could stand deformation energies of 22.3 ± 1.7 kJ, 22.0 ± 3.4 kJ and 22.1 ± 1.3 kJ, respectively. These values are approximately 19 times higher compared to adhesive bonded reference joints. The similarity in deformation energy containing pin arrays allows for the conclusion that deformation energy primarily depends on the amount of installed pins, but not on arrangement of the pins.

4 Conclusions and Outlook

It was shown that metallic pins with small dimensions can be produced in a fully automated manufacture process on thin metal inserts via a modified cold metal transfer process. The use of ballhead pins with a spike on top improves both the drapability and the reinforcement of joining areas in CFRP to CFRP SLS joints.

The use of reinforcing pins increases failure stresses and changes damage tolerance distinctively compared to adhesive bonded specimens. This is reached without the need to cut fibers or drill holes and without a significant increase of structural weight also.

The arrangement of pins near the outer edges of the metal inserts leads to high first failure stresses whereas the alignment of pins close to the center leads to higher failure strengths. The arrangement of
pens has no distinct influence on the level of total deformation energy, only the number of pens. Future investigations will focus on metal inserts with pens made of titanium both in single lap shear and double lap shear joint configurations. Furthermore, the comparison of load bearing capacities with reference joints will be done under tensile loading, both static and fatigue. Fracture mechanical investigations will also be done on pin reinforced double-cantilever beam and end-notch flexure CFRP specimens.

6 Acknowledgements
The funding of the Austrian Research Promotion Agency for project 830384 “Composite+composite Joints with Enhanced damage tolerantCe (CoJEC)” is gratefully acknowledged as well as the support of the involved project partners. Installation of the welding robot by Martin Schickbauer at Fill GmbH and calibration of the welding machine by Andreas Waldhoer from FRONIUS International GmbH are gratefully acknowledged.

5 References


