COMPOSITE TO COMPOSITE JOINT WITH LIGHTWEIGHT METAL REINFORCEMENT FOR ENHANCED DAMAGE TOLERANCE

S. Ucsnik[a*], S. Stelzer[b], H. Sehrschön[c], G. Sieglhuber[c]

[a] *LKR Leichtmetallkompetenzzentrum Ranshofen GmbH, Austrian Institute of Technology, 5282 Ranshofen, AUSTRIA*
[b] *Montanuniversität Leoben, 8700 Leoben, Otto Glöckel-Straße 2/II, AUSTRIA*
[c] *Fill GmbH, 4942 Gurten, Fillstraße 1, AUSTRIA*
* *stephan.ucsnik@ait.ac.at*

Keywords: COMPOSITE JOINT, Z-PINNING, METAL, REINFORCMENT

Abstract

The increasing maturity of fibre reinforced plastics (FRPs) has led to the need for appropriate joining technologies for enhanced lightweight structures.
This research work presents the FRP joining and reinforcement concepts "CMT pin" and "Sheet pin". Tensile tests of "CMT pin" and "Sheet pin" reinforced joint specimens are presented. Results are compared to titanium z-pin or unreinforced references.
The 3D-shaped reinforcement elements do build up a beneficial form-fit with the CFRP components. This leads to distinct increase of mechanical joint properties. This research work proves a beneficial support and enhancement of "CMT pin" and "Sheet pin" reinforced / joint CFRP components.

1. Introduction

The trend towards multi-material lightweight design, including high amounts of fibre reinforced plastics (FRP), has recently led to light and efficient alternatives in aeronautic, (A380/350, Boeing 787), naval and automotive industries (Porsche Supercup, Bentley Mulsanne). In automotive industries, FRPs have been of minor importance for primary structure parts for the production of high volume cars. This has changed with the official roll-out of the "i-series" of BMW.

Together with the development and increasing maturity of FRPs, the need for appropriate joining technologies arose for the realization of integral assembly concepts and enhanced lightweight composite structures. At present, adequate high resilient, damage tolerant but fail-safe FRP joints or peel loaded FRP reinforcements are realized through established joining technologies like riveting or bolting, optionally combined with adhesive bonding and sealing.

The introduction of bolts or rivets requires the drilling of holes and therefore a cross-section reduction of the FRP components. Additionally, the joining elements lead to an increased assembly weight, especially the additional fail-safe connection points. Single adhesive-bonded or co-cured joints would be the lightest opportunity for joining FRPs, but they possess a far too less damage tolerance after first failure occurrence. Patterson [1] gives an overview of state-of-the-art joining technologies for composite applications in aeronautic industries. Figure 1 shows examples for a riveted, double-lap-shear composite shell connection and for a co-cured T-stringer connection

Bolt or rivet connections are optionally bonded in the touching interface. The adhesive bonding increases the initial joint stiffness, elongates the fail-safe-lifetime and builds an additional sealant on the touching surfaces.

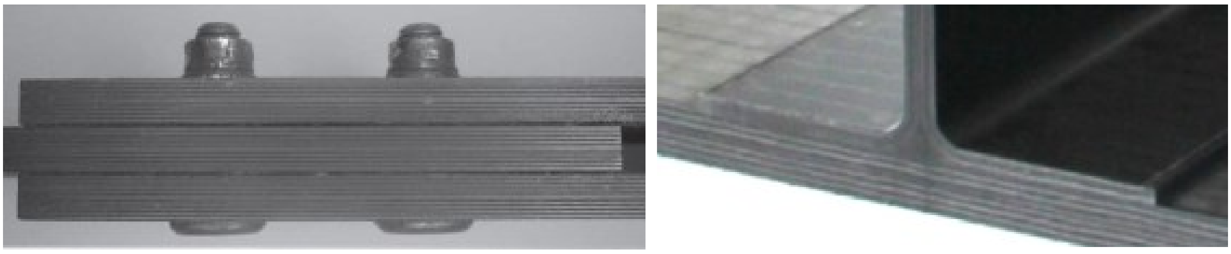


Figure 1: Riveted CFRP connection (left) [2], Co-cured T-stringer CFRP connection (right) [4]

Major disadvantages of state-of-the-art technologies are the cutting of reinforcement fibers due to the drilling process, the weakening of the composite cross-sections or a very low damage tolerance in case of adhesive-bonding. The amount of metal joining elements introduces mass, especially additional safety elements for elongated fail-safe-lifetimes. These negative aspects reduce the material utilization of parent FRPs what leads to an increased energy consumption.

New techniques pursue the concept of joining or through thickness strengthening of fibre reinforced components by so-called Z-Pinning with arrays of precured CFRP fibres (see Figure 2, left). In Z-Pinning, CFRP fibres are installed through the thickness of dry or pre-impregnated laminates. After curing of the matrix resin, these pins strengthen the laminate in the out of plane direction. The concept of Z-Pinning was developed in the early 1980s. Since then it was extensively investigated and improved [2 - 7].

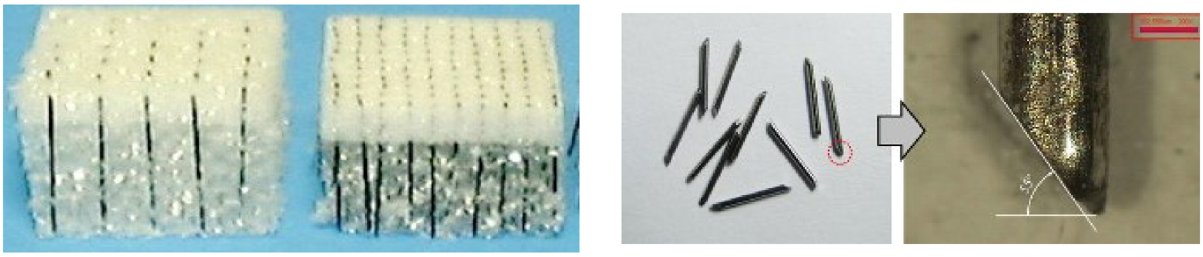


Figure 2: Foam Core with CFRP Z-pins (left), and steel Z-pins (right) [8, 12]

Z-Pinning is also known with high-grade steel rods (Figure 2, right). Early investigations are known by Karpov [9, 10] and Kolesnikov [11]. Recent studies have been led by Son and Hun Ji [12, 13]. Compared to CFRP Z-pins, metal Z-pins are insensitive towards elevated temperatures and humidity and material and production costs are far less. Nevertheless, steel rods lead to an additional weight input and additional surface pretreatments are needed to achieve a good adhesive bonding between the steel rods and the laminate.

Besides the improvement of the damage tolerance and fail-safe-lifetimes of adhesive bonded FRP joints, z-pinning with CFRP or metal rods leads to the improvement of the Mode I and Mode II fracture properties. In special, this turns out beneficial for peel stressed, shear stressed and delamination endangered composite sections, i.e. the transition zones between horizontal base shell and vertical stringer section (see Figure 1, right).

Most dominant negative point of FRP joints with bolts or rivets is the high introduction of additional weight. In case of Z-pinning disadvantages exist in the failure mode of the Z-pins.

After failure of the adhesive bonding, Z-pins slip out of the composite due to missing form-fit and interlocking between the reinforcement elements and the surrounding FRP. If a form fit between the small-diameter reinforcement elements and the FRP could be established, the fracture properties and connectivity would be further enhanced. This would end up in a higher material utilization.

Novel joining and reinforcement technologies aim at establishing both the joint between single FRPs and the reinforcement of FRPs through the thickness by an interleaving-reinforcement concept (IRC). IRC works with thin metal inserts which possess 3-dimensional shaped joining surfaces. In there, the 3D-shaped joining surfaces of the metal reinforcement elements and the parent metal substrate have a carrier function. One representative of IRC is the RHEA Technology investigated by Nogueira et al. [14-16]. In there, reinforcement elements of metal inserts are realized through a role punch process which are finally bent up- or downwards out of the insert plane.

The combination of the advantageous of afore mentioned joining technologies would result in joining elements of low mass. These would consist of a carrier sheet with small-size, vertical reinforcement elements, coaxial aligned on top and bottom side. The reinforcing elements would show undercut geometries which are beneficial for the form-fit with the opponent FRP. Until present, such joining elements are not available.

This research work presents two new IRC alternatives developed at the author's research institution in collaboration with industrial partners. The underlying concepts of the reinforcement inserts and their manufacture methodologies are explained. Quasi-static tensile tests of IRC reinforced joint specimens are presented and compared to unreinforced and titanium rod z-pinned references.

2. Novel IRC Technologies

2.1. CMT Pin Insert

The first technology, developed at the author´s research institution in collaboration with industrial partners, utilizes the CMT-pin process by FRONIUS for the manufacture of 3D-shaped metal reinforcement elements (pins) on the metal substrate [17]. Figure 3 (left) shows a stainless steel sheet (AISI 306L) with a thickness of 0.6 mm. This possesses arrays of 2x6 pins on the leading and trailing edge of the sheet. Pins are coaxial aligned on top and bottom sheet surfaces (Figure 3, right). This builds a direct load transfer through the pins without affecting the carrier sheet. Figure 3 (right) shows the form-fit between pins and the CFRP.

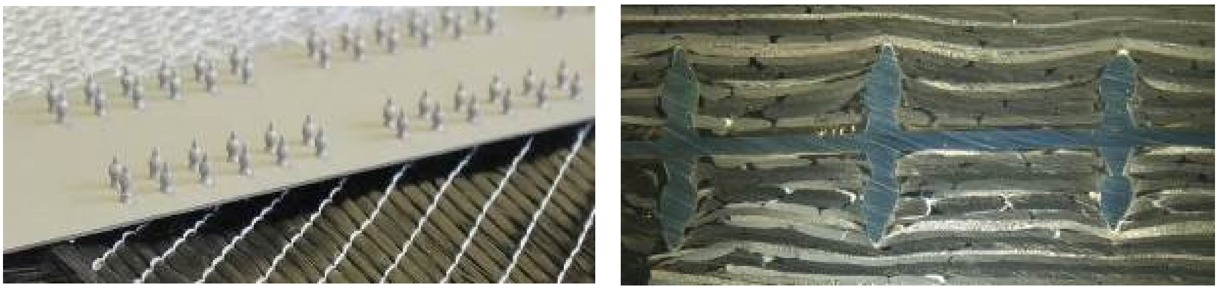
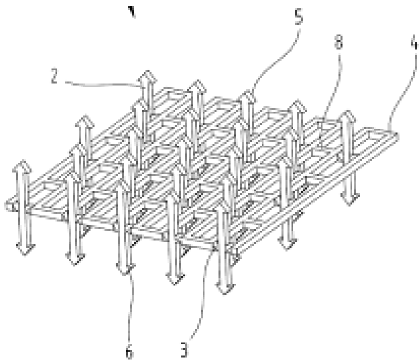


Figure 3: Thin stainless steel insert with arrays of CMT pins (left), cross-section of aligned CMT pins in CFRP laminates (right) [17]

2.2. Sheet Pin Insert

The second technology developed, deals with a patented insert technology [18]. This allows realizing 3D-shaped elements similar to [14-16] but with the advantage of having top and bottom reinforcement elements coaxially aligned after the bending process. This is realized through a special cutting pattern for the reinforcement elements. The elements are cut out of the sheet, but at the turning point of the reinforcement element a connection is left to the substrate metal. At rotation of the reinforcement element out of the sheet plane, only the connection points face deformations and strains. The reinforcement element itself remains unaffected and maintains its original material properties. Figure 4 shows the concept of the insert technology and one final finished insert (stainless steel, sheet thickness t = 0.6mm).



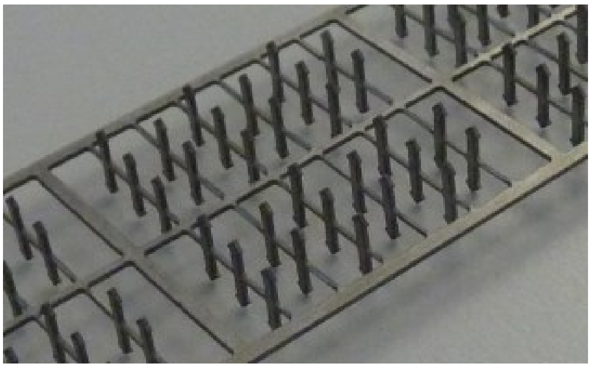


Figure 4: Novel IRC insert (left), final finished insert with 2x6 pins at the leading and trailing edge (right)

Both concepts allow for the realization of coaxially aligned reinforcement elements with 3D-shaped geometries on top and bottom side of the insert. In the case of CMT-pin, the maximum number of pins on the insert depends on the minimum achievable allowable pin distance. Disadvantageous might appear due to thermal induced distortions of the thin sheet due heat input and stress release due to the welding. In the case of the new bending concept, the maximum number of reinforcement elements depends on the overall insert dimensions, but complex reinforcement elements can be realized easily, the insert is not affected by the shaping or bending process, it does not face thermal process steps, and it can be utilized even at complex curved joining faces (convex, concave, combined).

3. Specimens and Mechanical Characterisation

SLS specimens are used for the characterisation of mechanical properties of the CFRP-joints. The materials used in this study are high tenacity, standard modulus, biaxial non-crimp carbon textiles from Toho Tenax and Hexflow® RTM6 as epoxy resin from Hexcel Composites with a symmetric laminate stacking sequence $[0/90/\pm45/90/0/\pm45/90/0]_s$ for quasi-isotropic material properties. Metal inserts are made of stainless steel type AISI 304 with a sheet thickness of t = 0.6 mm.

The specimens have overall dimensions of 190 x 25 x 10 mm and an overlap length of 30 mm. Figure 5 shows the shape of one SLS joint with an interleaving reinforcement insert.

Figure 5: Sectional view of a SLS joint specimen with an interleaving reinforcement insert between the single CFRP laps.

In the case of the CMT-pin inserts, arrays of 2x6 ballhead spike pins are made of a filler wire type AISI 316L with a diameter of 0.8mm (see Figure 3 right). Final pins have a foot diameter of 1.2mm, a shaft diameter of 0.8mm, and an overall height of 3.3 mm [17].
In the case of sheet pin inserts, 2x6 pins have a cross-section of 0.60 x 0.84 mm and an overall height of 3.0mm (see Figure 4 right). With the selected cross-section dimensions, the area of one pin is equal to the cross-section of a CMT-pin. This allows a direct comparison of force results in the subsequent data evaluation in section 4.

Z-pin reinforced and co-cured joint specimens are used as reference. Z-pin reinforced joint specimens are manufactured equally to CMT-pin and sheet pin insert reinforced specimens. Only, the inserts are realized in a different manner. The metal inserts consist of 0.4mm thick, pre-drilled titanium sheets in which pieces of titanium TiAl64 rods of diameter 0.76mm are installed through press-fit (see Figure 6 left). They possess a spherical ending but with no undercut. Co-cured reference samples are manufactured equally to reinforced joint samples but without the implementation of an interleaving reinforcement insert.

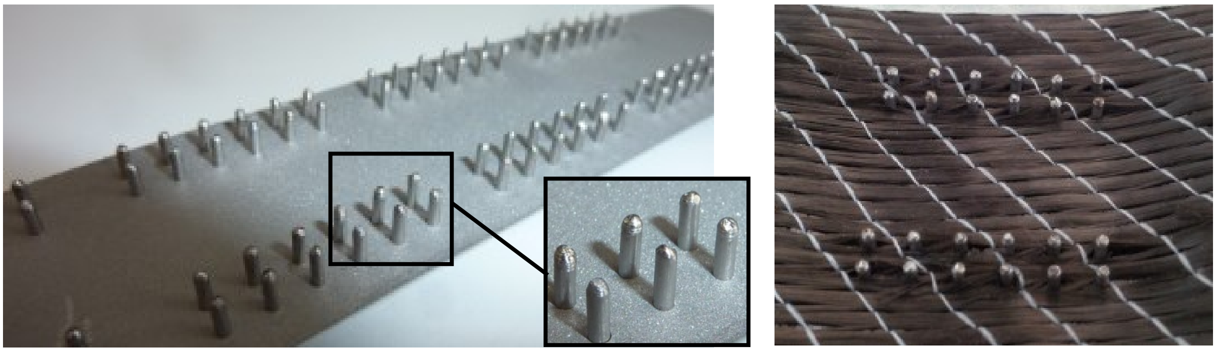


Figure 6: Reinforcement inserts with 2x6 titanium z-pins at leading and trailing edge of the insert (left). Z-pins penetrating dry carbon textiles during draping (right).

The joint specimens are tensile tested on a servo-hydraulic test machine, MTS 322, with a load range of 250 kN. Joint reaction forces and crosshead displacement are recorded on the tensile test machine. Local joint expansions are recorded by using an optical deformation measurement system. Two points are tracked on the CFRP-joint specimens, each of the points being located in the middle of one CFRP lap in a distance of 10mm away from the overlapping joint area. A minimum of 5 samples is tested for each batch of joint samples.
In the following graphs recorded reaction forces are plotted over local joint expansions.

4. Results and Discussion

Figure 7 shows mean graphs of tension tests of the various batches of CFRP SLS joints.
In the case of the co-cured references (Figure 7, full line), the reaction forces follow a linear increase up to mean maximum forces of 9.80kN ±2.0% and joint expansions of 0.22mm. The joints fail instantaneously without any sign of non-linearity or crack initiation at an absorbed energy of 1.03J.
This is distinctively different to the z-pin reinforced reference joints (Figure 7, dotted line). At the very beginning, these joints show a linear increase of forces up to 3.8kN. This is followed by a non-linear load transfer up to a mean maximum force of 5.94kN ±0.1% and joint elongations of 1.12mm. After a slight decrease in reaction force, a continuous failure-behaviour sets in. At the point of maximum force, the joints absorbed a total energy of 4.24J.
Z-pin reinforced SLS-joints possess a distinctively higher energy absorption capability (4.11 times higher) which in turn stands for an enhanced damage tolerance of the joints.

Nevertheless, z-pin reinforced joints cannot reach the level of maximum forces of co-cured reference joints (–39.3%). This is due to the weak adhesive bonding between the CFRPs and the interleaving z-pin insert and the missing form-fit with the CFRP.

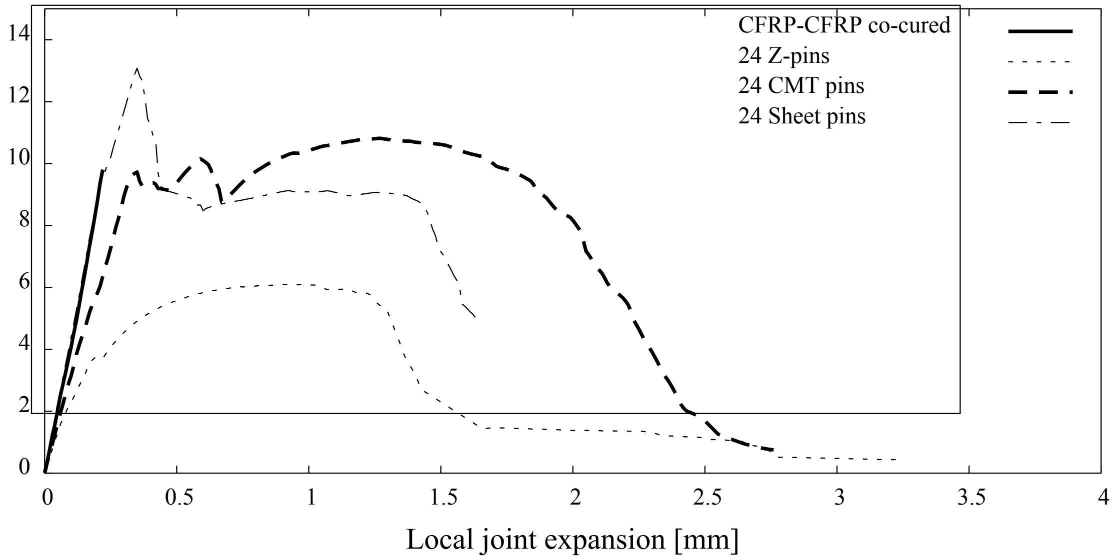


Figure 7: Graphs for the reference specimens: co-cured reference (full line), titanium z-pins (dotted line)

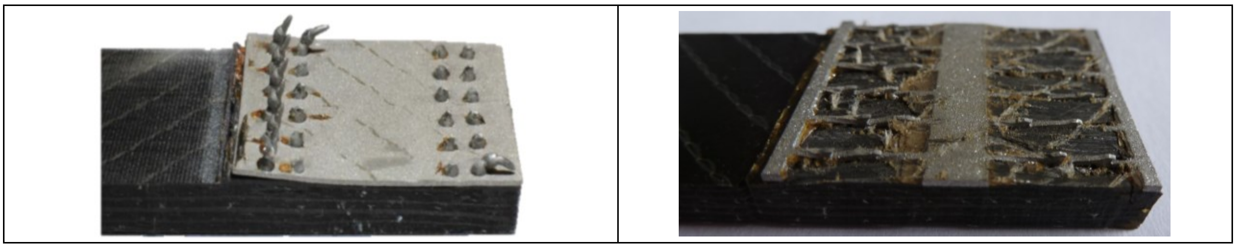


Figure 8: Failure shapes of CMT-pin reinforced CFRP joint (left) and sheet pin insert (right).

4.1. CMT Pin Insert

The combined approach of adhesive bonding and form-fit, through beneficial shaped CMT pins, leads to a distinct improvement. The respective graph of CMT pin reinforced joint specimens (Figure 7, thick, dashed line, "24 CMT Pins") follows a slightly decreased slope up to a first mean peak of 9.73kN ±17.9% at local joint expansions of 0.37mm. The initial stiffness is 37% less compared to the co-cured reference. After the first initial force peak, joint forces face a further, non-linear increase up to mean maximum joint forces of 10.82kN ±2.4% at joint expansions of 1.27mm. At this point the joints absorbed an average energy of 10.82J. CMT pin reinforced specimens finally fail in a continuous manner due to the ductile shearing of the pins.

Figure 8 (left) shows a failed joint section of a CMT pin reinforced CFRP joint. Three out of four rows of pins have been sheared off at the smallest diameter of the pins, just above the conical feet.

4.2. Sheet Pins Insert

The respective graph of sheet pin insert reinforced specimens (Figure 7, thin, dash dotted line, "24 Sheet Pins") follows the same slope as the co-cured reference up to 9.8kN at 0.22mm. Joint forces rise further up to mean maximum forces of 13.08kN ±2.9% at joint expansions of 0.35mm. At this point, the joint absorbed about 2.54J which is already 1.5 times higher

compared to the co-cured reference with 1.03J. After passing peak joint forces, the forces drop down to a mean value of about 8.7kN which can be held until local joint expansions surpass 1.4mm. Up to this point the sheet pin insert absorbs 10.8J.
Figure 8 (right) shows a failed joint section of a sheet pin reinforced CFRP joint. All pins are sheared off at the bottom of the pins.

Figure 9 gives a comparison of the linear joint forces F_{linear} (the point of a first slope change), the mean maximum joint forces F_{max} and the absorbed energies $E_{absorbed}$ at point of F_{max}. In case of “24 Sheet Pins”, afore stated value of $E_{absorbed} = 10.8J$ is used for comparison.
In comparison to co-cured references, CMT-pin and Sheet-pin reinforced CFRP-joints show equal F_{linear} and higher F_{max} values (+10.4% and +33.4% respectively). When comparing the absorption energies, tremendous increases by a factor of bigger than 10 can be noticed.

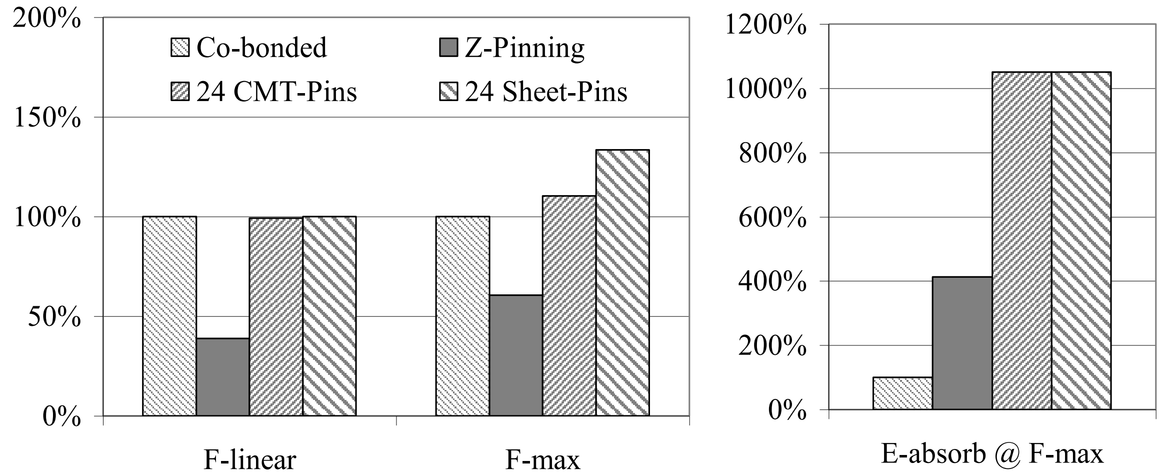


Figure 9: Comparison of joint forces and absorbed energies for the differently reinforced CFRP joints.

5. Conclusions

This research work leads to the conclusion that 3D-shaped reinforcement elements must have an undercut geometry to achieve a beneficial support and enhancement effect for IRC insert reinforced CFRP joints.
Metal z-pins build up a vertical interaction with the single CFRP layers and an adhesive bonding with the CFRP. Compared to co-cured reference joints, z-pin inserts lead to higher absorption energies but not to higher joint forces (see Figure 9). This is due to the lack of capability for building up an additional constraint through form-fit with the CFRP. The comparison of results of CMT pins and sheet pins reinforced joints with the reference shows that both CMT pins and sheet pins do have the capability of building up the beneficial form-fit with the CFRPs. This leads to distinct increases of the maximum transferable joint forces as well as the absorption energies hence damage tolerance of the joints.
The present study is based upon metal reinforcement inserts with a total number of 24 pins coaxially aligned on the insert surfaces. However, the mechanical properties of the investigated CFRP joints and hence the material utilization can be further raised by increasing the number of installed pins on the inserts.
Initial investigations have proven that sheet pin inserts are an adequate alternative to z-pin or CMT pin inserts for the reinforcement or connection of CFRP components. Sheet pin inserts have not only lead to equal or exerted mechanical properties of the CFRP joints. They are also flexible, cheap and easy in terms of handling.

References

[1] E. Patterson et al. *Composite Materials and Joining Technologies for Composites*, volume 7, 2012.
[2] F. Liu et al. A modified failure envelope method for failure prediction of multi-bolt composite joints. *Composites Science and Technology*, 83(0):54 – 63, 2013.
[3] S. Heimbs et al. Failure behaviour of composite T-joints with novel metallic arrow-pin reinforcement. *Composite Structures*, 110(0):16 – 28, 2014.
[4] D. Cartiaé et al. 3D reinforcement of stiffener-to-skin t-joints by Z-pinning and tufting. *Engineering Fracture Mechanics*, 73(16):2532 – 2540, 2006. Fracture of Polymers, Composites and Adhesives.
[5] A.P. Mouritz. Review of Z-pinned composite laminates. *Composites Part A: Applied Science and Manufacturing*, 38(12):2383 – 2397, 2007.
[6] F. Bianchi et al. Finite element modelling of Z-pinned composite t-joints. *Composites Science and Technology*, 73(0):48 – 56, 2012.
[7] T.M. Koh et al. Strengthening mechanics of thin and thick composite T-joints reinforced with z-pins. *Composites Part A: Applied Science and Manufacturing*, 43(8):p.1308, 2012.
[8] D. Cartiaé et al. Delamination of Z-pinned carbon fibre reinforced laminates. *Composites Science and Technology*, 66(6):855 – 861, 2006.
[9] Y. Karpov. Jointing of high-loaded composite structural components. Part 1. Design and engineering solutions. *Strength of Materials*, 38:234 – 240, 2006.
[10] Y. Karpov. Jointing of high-loaded composite structural components. Part 3. An experimental study of strength of joints with transverse fastening microelements. *Strength of Materials*, 38:575 – 585, 2006.
[11] B. Kolesnikov et al. Fortschrittliche Verbindungstechniken von Faserverbundstrukturen. *Tagungsband des Deutschen Luft-und Raumfahrtkongresses (DGLR)*, 09 2004.
[12] H.G. Son et al. Fatigue behaviour of metal pin-reinforced composite single-lap joints in a hygrothermal environment. *Composite Structures*, 108(0):151 – 160, 2014.
[13] H. Ji et al. Fatigue characteristics of stainless steel pin-reinforced composite hat joints. Composite Structures, 108(0):49 – 56, 2014.
[14] A.C. Nogueira et al. Properties and failure mechanisms of a 3D-reinforced joint. *JEC magazine*, 69:p. 39, Nov.-Dec. 2011.
[15] A.C. Nogueira et al. Investigation of a hybrid 3d-reinforced joining technology for lightweight structures, *in Proceedings of 16th International Conference on Composite Structures ICCS16*, Porto, P, 2011.
[16] A.C. Nogueira et al. Static and fatigue strength of a damage tolerant 3D-reinforced joining technology for composites. *In 12th European Conference on Spacecraft Structures, Materials and Environmental Testing*, Noordwijk, NL, 2012.
[17] S. Stelzer et al. Novel composite-composite joining technology with through thickness reinforcement for enhanced damage tolerance. *In Proceedings of 19th International Conference on Composite Materials*, Montreal, Canada, 28th July - 2nd August 2013.
[18] H. Sehrschön et al. *Patent A2013 / 50492* Verbindungselement, 2013.

Acknowledgement

The authors thanks the Austrian Research Promotion Agency (FFG), the Federal Ministry for Transport, Innovation and Technology (BMVIT) and Austrian Institute of Technology (AIT) for the financial support as well as the project partners FACC (in special Jürgen Tauchner), Fronius, Rübig, Fill, RECENDT, Montanuniversität Leoben for the financial and technological support of project "Composite –composite Joints with Enhanced damage toleranCe – CoJEC" in the framework of the funding program TAKE OFF.