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Strength and damage tolerance of composite–composite joints with steel and titanium through the thickness reinforcements

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ABSTRACT

Today's aeronautic, automotive and marine industry is in demand of structurally efficient, low weight alternatives for composite–composite joints which combine the advantages of low weight input of adhesively bonded joints and high damage tolerance of through the thickness bolted joints. In the present work, composite–composite joints are reinforced through the thickness by thin metal inserts carrying cold metal transfer welded pins (CMT pins). The influence of pin alignment and type of pin on the damage tolerance of single lap shear (SLS) composite–composite joints is investigated. The use of titanium reinforcements is evaluated and compared to stainless steel reinforced, adhesively bonded and co-cured specimens. A detailed analysis of the stress–strain behavior is given and the stiffness and energy absorption of the SLS joints during tensile loading is assessed. The results show that joints reinforced with CMT pins absorb significantly higher amounts of energy, when compared to adhesively bonded and co-cured joints.

1. Introduction

Joining and through the thickness reinforcement of carbon fiber reinforced composites (CFRP) have been topics of increasing interest in recent years. This increasing interest originates from disadvantages of conventional joining technologies such as rivets, bolts or screws. Such disadvantages can be the reduction of substrate cross-section due to boreholes, stress concentrations around boreholes, cutting of continuous fibers due to drilling, or additional weight input due to joining elements and additional safety elements [1–3].

Adhesive bonding, a bolt-free alternative for composite joints, provides joints at a very low weight input without the requirement to cut fibers. However, adhesively bonded joints are sensitive to out-of-plane and peel stresses. At present, adhesively bonded joints are not considered for use in primary composite aircraft structures due to difficult quality control and certification issues. Rivets and bolts are commonly used to provide a load path redundancy in adhesively bonded joints. On the one hand, this increases the joint weight. On the other hand it weakens the composite material [4].

Generally, joints have to simultaneously optimize several properties like e.g. to reduce weight, increase strength and/or damage tolerance, increase ductility, increase technical feasibility, ease manufacturing and/or reduce cost. Structurally efficient, low weight alternatives for conventional composite joints, which positively combine as many of these aspects as possible, have the potential for application in composite structures.

Many researchers have investigated the capability of carbon fibers [5–12], polymeric yarns [13–16], and glass fibers [9,17] for interlaminar reinforcement for CFRP laminates. They concluded that polymeric yarns, carbon fibers and glass fibers add to the damage tolerance of the laminate predominantly by crack bridging and energy absorption during pullout of the fibers from the matrix resin [5–13]. Investigations on metal reinforcements [4,12,18–24] have shown that such elements can additionally add to the damage tolerance by plastic deformation of the metal reinforcement [22–24].

The applicability of metal reinforcements to composite–composite joining was investigated by various research groups. Rugg et al. [25] carried out SLS tests on composite–composite joints, which were reinforced with metallic rods. These rods were angled nominally at 45° to the plane of the laminate. In tensile loading, all of the rods were pulled out, regardless of rod orientation (+45° or −45°). This pull out happened at relatively low loads and had little effect on the damage tolerance of the SLS joint.

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Cartié et al. [26] studied the influence of the insertion angle of both carbon and titanium rods on the fracture mechanical behavior of through the thickness reinforced CFRP. They concluded that failure mechanisms are dominated by the following effects: (1) debonding and subsequent pull-out (2) rod/substrate friction, (3) deformation of the rods, and (4) ploughing of the rod through the matrix material. In shear loading, these mechanisms depend on the insertion angle of the rods, giving a transition from pull-out dominated failure mechanisms to rod dominated failure. Rod failure led to the highest failure loads. In shear loading, titanium rod reinforced samples gave higher peak loads and ultimate deformation values than carbon rod reinforced samples. In tensile (pull out) loading, titanium and composite rods yielded a similar load displacement behavior.

Metallic through thickness reinforcements can add to the damage tolerance of composite–composite joints. Due to higher shear strength properties compared to carbon composites they can even surpass the reinforcement effect of carbon rod reinforced composite–composite joints. To further increase the joint strength and the damage tolerance of through thickness reinforced composite joints, pull out of through thickness reinforcements needs to be suppressed.

Research groups at Airbus Groups Innovation [22,23,26–28] use the so-called RHEA (redundant high efficiency assembly) technology to reinforce composite–composite joints in the through thickness direction. RHEA is based on the use of thin metallic sheets, where the pin geometry is laser-cut and bent to obtain reinforcement sheets with staggered pins and hooks on top and bottom surfaces. The pins provide a mechanically interlocking connection between the metal reinforcement inserts and the surrounding CFRP.

Tests on T-joints led to increased residual forces after delamination initiation at the spar-skin interface [22]. This resulted from a crack bridging zone formed by the metallic pins at the debonded interface.

The metal inserts technology, used in the RHEA technology [22,23,26–28], does not provide the possibility for coaxially aligned pins on the top and bottom side of the insert surface. The pins are not co-axially aligned and thus do not provide a straight load path from top to bottom side in the joined composites. However, a non-straight load path may result in a more complex stress field and a more complex damage behavior. This may trigger crack branching and hence a beneficial damage behavior and has yet to be investigated.

Graham et al. [19] as well as Parkes et al. [29] produced metallic pins with a 3D geometry on solid metal parts by additive layer manufacturing (ALM). They then joined the metal part to a CFRP part and carried SLS tests under monotonic loading conditions. They observed significant increases in strength and damage tolerance. In a more recent work, Graham et al. [30] replaced ALM by stud welding due to manufacturing cost and time reasons. They compared pinned SLS joints to co-cured SLS joints under monotonic loading and again observed significant increases in strength (+80%) and energy absorption (+1000%).

Ucsnik et al. [31–34] carried out thorough investigations in the fields of metal to CFRP joining by using the cold metal transfer (CMT) welding process for surface shaping invented by Fronius International GmbH (Pettenbach, A) [35]. This knowledge was transferred to the "surface treatment" of thin metal sheets with 3-dimensional pins on the top and bottom surface. Similar to RHEA, such metal inserts can be used to join and reinforce CFRP to CFRP joints (Stelzer et al. [18,36]). In contrast to RHEA inserts, CMT shaped inserts do provide the possibility for coaxially aligned pins. These in turn allow for a direct, non-staggered load transfer from top to bottom composite part through the metal pins.

The present work deals with the determination of the mechanical properties of CMT pin insert reinforced CFRP to CFRP joints. The focus is put onto SLS joints which are reinforced with steel or titanium inserts that carry arrays of 3D shaped, co-axially aligned pins on top and bottom side.

2. Experimental

2.1. Materials and specimens

All composite joint specimens were made of high tenacity, standard modulus carbon fibers from Toho Tenax (Tenax® HTS, Saertex® biaxial non-crimp fabric, 540 g/m^2 areal weight) and epoxy resin from Hexcel Composites (Hexflow® RTM6). All laminates possessed a quasi-isotropic stacking sequence of $[0/90/\pm45]_{5s.}$ The metal reinforcements were made of either stainless steel or titanium. In the case of stainless steel, inserts type AISI 304 with a sheet thickness of $t = 0.6$ mm were used. These carried arrays of ballhead spike pins, a combination of a ballhead pin with a small spike pin on top of it. They were made by cold metal transfer (CMT) welding a filler wire type AISI 316L with a diameter of 0.8 mm. The titanium inserts and pins were made of Ti6Al4V. The titanium sheets had a thickness of 0.4 mm and the filler wire a diameter of 0.8 mm. For CMT welding the steel pins, a shielding gas consisting of 95% Argon and 5% CO_2 was used. For CMT welding the titanium pins pure Argon was used as a shielding gas.

SLS specimens of a first test campaign were reinforced with steel inserts which had three different arrangements of 4 × 6 ballhead spike CMT pins co-axially aligned on top and bottom surface (Fig. 1). Array 1 had an equal distance arrangement (Fig. 1a). Four rows, each with six CMT pins, were equally distributed with a pitch of $p_x = 7.0$ mm, starting 3.0 mm away from the free edges of the metal insert (x being the axial loading direction). The CMT pins had a lateral pitch of $p_y = 4.2$ mm (with y indicating the lateral direction). For array 2, the CMT pins were primarily arranged at the end positions of the inserts. The outer two rows of 6 CMT pins were positioned each 1.5 mm away from the free edges of the metal insert with a pitch of $p_x = 3.0$ mm to the second rows (Fig. 1b). For array 3 the CMT pins were clustered at the four corners of the insert in a triangular shape (Fig. 1c). The pins had an equal pitch of $p_x = p_y = 3.0$ mm.

Fig. 2(a) shows a stainless steel insert with pin array type 1 after the CMT pin welding process. The steel CMT pins had an overall height of about 3.3 mm and a tapered shaft with a diameter of about 1.2 mm at the bottom and 0.8 mm below the ballhead. Titanium inserts had the same arrangement of pins as the steel inserts of pin array type 2 (Fig. 2b and c). For comparison reasons, two types of titanium inserts were produced with pieces of titanium rods as vertical reinforcement elements (Ti z-pin, Fig. 2c) in addition to CMT welded titanium pin inserts (Ti CMT pin, Fig. 2b). The Ti CMT pins had a height of 1.85 mm. Their shaft and head had diameters of around 0.9 mm and 1.6 mm respectively. Ti z-pins had diameters of 0.76 mm and 1.14 mm and a height of 3.5 mm each. These pins were press fitted into predrilled titanium sheets.

Prior to the draping process all inserts were surface treated by cleaning and sandblasting. This helped to remove contaminations such as grease and welding tinder and to increase the roughness of the metallic surface. This is considered to be beneficial for the adhesion between the metal and the epoxy resin. In a final step the inserts were cleaned with an organic solvent.

For the preforming process, the metal sheets were reproducibly fixed in a metal mold. A set of dry CFRP textile layers was draped onto the top and bottom pin arrays in a symmetrical manner (Fig. 3), so that quasi-isotropic laminate properties were achieved. CFRP specimen-panels were produced via a liquid resin infusion process.