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3D-reinforcement techniques for co-bonded CFRP/CFRP and CFRP/metal joints: a brief review

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Abstract

The present paper will make a brief review on some of the most relevant through-thickness reinforcement technologies for CFRP/Metal and CFRP/CFRP joints developed so far. A distinction between the traditional ("*z-pinning*" and "*stitching and tufting*") and novel ("*COMELD*^{TM}", "*CMT*", "*HYPER*" and "*RHEA*") 3D-reinforcement techniques will be made and the most relevant characteristics of each one will be pointed out.

Keywords: CFRP; joints/joining; z-reinforcement; damage tolerance.

1. Introduction

In the past few years, a huge effort has been made in the aeronautics industry regarding design and assembly of structural parts. The purpose is to get lighter structures, enhance performance and critically reduce fuel consumption. Hence, new materials concepts offering weight savings and better performance are in high demand.

Composite systems have been known for many years, but only recently they have been used in full scale structural components. The usage of such materials for aircraft structural applications is basically confined to carbon fibre reinforced polymers (CFRPs). With flexible and easy fabrication processes, CFRPs can achieve relevant characteristics such as high specific stiffness and strength, dimensional stability, corrosion resistance, electrical conductivity, and even good fire/smoke performance [1]. In civil aircraft, structural content of CFRP has surpassed the 50 wt.% level with the introduction of the AIRBUS' A350 XWB and the BOEING's 787 and the trend is that this value continues to increase. Development of laminated composite systems for aircraft applications brought up new challenges. A major concern has been to establish effective assemblies between fibre-reinforced polymer (FRP/FRP) parts or FRP/metal parts. FRP present anisotropic properties whilst metals are generally isotropic. They also present different thermal expansion coefficients and substantially different technologies are used to produce the parts.

Joining of composite materials to themselves or other dissimilar materials is currently done by three methods: adhesive bonding, mechanical fastening or a combination of bonding and fastening [2].

Mechanical fastening represents the primary joining technique for composite structures due to the thorough knowledge and reliability achieved in the past for metallic structures. However, its use for joining composite parts is not as straightforward as for metals [3]. The installation of fasteners which requires drilling of FRP parts results in stress concentrations around the holes due to the lack of plasticity and high notch-sensitivity exhibited by these materials. Low sealing performance, weight addition, great costs and complex failures modes represent also major challenges for designing proper mechanically fastened

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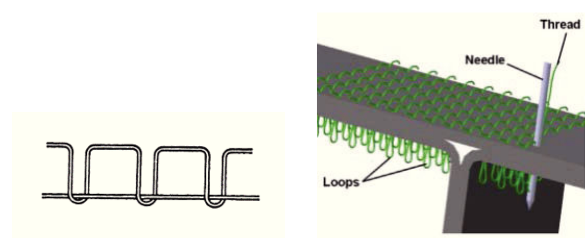
joints.
Adhesive bonding emerged in the early 50's, as a gentle, non-destructive joining technique for two different materials. Notwithstanding many advances, problems like sudden failure of the joint, poor out-of-plane properties, need for relatively large bonding areas and lack of appropriative non-destructive testing (NDT) methods required the development of new joining technologies that are more damage tolerant than pure adhesive bonding [4].
Employment of safety rivets and bolts in combination with adhesive bonding is an alternative, but this imply destruction of fibres and weight increase, further to cost increase due to the drilling process of thousands of holes for all the joints in an aircraft structure.
Progresses in a variety of through-thickness reinforcement techniques for composite structures have been made recently. The concept of improving the toughness and strength of CFRP/CFRP and CFRP/Metal joints is not a latter-day issue. In the early 90's, several technologies ("stitching", "tufting", "3D weaving", among others) have come to light as effective Z-reinforcement techniques, where important properties were improved. However, at that time, only one technique- "z-pinning"- was suitable for reinforcing uncured pre-preg laminates, often used in aeronautics structures. This technique became quickly popular since properties like delamination resistance, out-of-plane stiffness and joint strength were highly enhanced. Nonetheless, such gains were only possible by sacrificing in-plane strength/elastic properties of the laminates itself. Furthermore, even when partially automated, this was still a lengthy and costly process. Therefore, new cost and time effective technologies, capable of reinforcing laminated composites through its thickness and improve joint performance have been intensively investigated. The goal is to achieve an effective bond between CFRP/CFRP and CFRP/Metal joints by combining adhesive bonding with the mechanical interlocking effect of the reinforcements without significant deterioration of in-plane properties.

2. Classical 3D-Reinforcement Techniques

2.1. Stitching and Tufting

Stitching involves sewing a high tensile yarn (carbon, glass or aramid) through the thickness of the laminate structure using a sewing machine [5]. Aramid and glass are the preferred materials to be employed as the reinforcement yarn [6] due to its greater flexibility. Prior to curing, a stack of plies is penetrated and locked together with the aid of a hollow needle and/or bobbin threads. The final stitched composite is then consolidated via resin film infusion or resin transfer moulding. Among the different styles of stitching, the modified lock stitch (Fig. 1a)) is the most popular because it is the one that causes less fibre distortions and therefore less weakening of in-plane mechanical properties [5]. However, even with this method, significant distortions of both in-plane fibres and fibres within the stitches are unavoidable as fibres are bended to accommodate the stitches, and stitches are crimped during laminate consolidation/compaction.
The fact that this technology uses a dual-threading system (upper and lower threads) to form the loops or knots makes it unrealistic for use in large/complex structural applications [6,7]. Hence, a more advanced technology, similar to stitching, was developed – "tufting". Tufting is a single-thread sewing method in which the formation of loops is possible with a loose and tension-free insertion of a threaded needle that has less adverse effects on the material (Fig. 1b)) [7,8]. The needle pushes the yarn inside the preform using an elastic foam tool and its removal is made along the opposite trajectory; thus, only access to one side of the structure is required. Prior to resin infusion, the thread pathway allows the formation of a loose loop that remains in place relying on the friction between the yarn itself and the host fabric preform. The actual reinforcement comes only after resin injection from the bonding between matrix and thread.



a) b)

Fig. 1. a) Modified lock stitch [5] and b) Tufting of a T-joint [9].

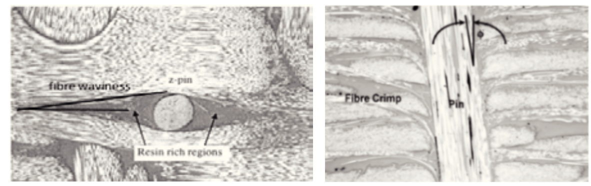
Stitching reduces in-plane properties by up to 20%, while drop-downs with the Tufting method are below 10% [5,8]. On the other hand "tufts" and "stitches" have shown to improve compression strength after low velocity and ballistic impacts of around 95% and 50%, respectively [10]. The presence of stitches on CFRP laminates was also found to improve the delamination resistance against crack propagation under both modes I and II of about 15 times and 4 times, respectively [11,12].

2.2. Z-pinning

The aforementioned technologies are only suitable for textile laminates made by using dry fabric plies containing the reinforcement prior to resin infusion. This is a serious limitation, especially when it comes to aircraft structures since many highly-loaded components are made using pre-preg laminates [13]. At that time, only one technology was capable of reinforcing pre-preg laminates along its thickness - “z-pinning”.

Z-Pinning was first patented in the early 90’s by the Aztex Corporation for reinforcing 2D laminates. Z-Pins or Z-Fibers™ are short rods or pins made from extruded wire material with high strength/stiffness, (titanium alloy, steel or fibrous carbon composite) that act as thin nails capable of locking the different laminate layers together by a combination of friction and adhesion. With this technology, access to only one side is possible, which is a great advantage in relation to other classical techniques. Z-pins are used in a diameter range of 0.15 to 1.0 mm and are present in laminates with a volume density in the range of 0.5 to 4%, which is equivalent to about 8 to 70 z-pins/cm^2 [13]. The most common manufacture process of z-pinned laminates is the UAZ® (*Ultrasonic Assisted Z-Fiber*) process that is well described in [14].

Z-Pinning is an effective and simple way to enhance delamination resistance, damage tolerance, out-of-plane stiffness and joint strength of pre-preg laminates. The bridging effects produced by z-pins can increase the delamination resistance of up to 160% and 100% under modes I and II loadings, respectively [15]. The improved delamination toughness also increases the impact resistance and reduces the damage area, with the z-pinned laminates displaying damage areas of up to 64% smaller than the unpinned laminates [16]. Suppression of very short delaminations is not within the expected benefits provided by this technique; this means that z-pinning is only effective in the propagation stage rather than the damage initiation stage. Residual compression-after-impact (CAI) strength is also improved by z-pinning, with the pinned laminates presenting approximately 45% higher residual strength than the unpinned counterparts. Important improvements in the z- properties of CFRPs, such as tensile modulus, can also be achieved by introducing z-pins, with the out-of-plane stiffness of such laminates being increased by 50% or more with relatively modest amount of pins (2~4% by volume) [17]. Effectively, such gains on the through-thickness properties are only possible by sacrificing the in-plane mechanical properties. Although a general agreement on the causes for deterioration of such properties exists, the extent of damage induced to the in-plane properties due to the presence of z-pins, reported on the available papers, is not consistent. To be able to understand the benefits and damage induced to laminates caused by z-pinning, a full understanding of the microstructural changes is essential (Fig. 2). It is believed that the harm induced to the in-plane elastic and strength properties is due to the microstructural damage caused by z-pinning, particularly fibre breakage, waviness and crimping, resin-rich zones, pin offset, swelling of the laminate and cure stresses (Fig. 2) [13].



a) b)

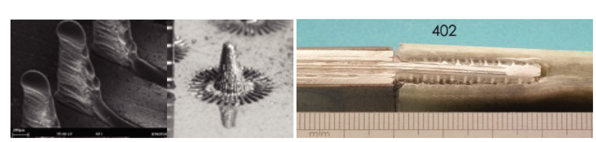
Fig. 2. Microstructural changes due to z-pins: in a) fibre waviness and resin rich zones, and in b) fibre crimp and z-pin offset [13].

3. Novel Reinforcement Technologies

3.1. COMELD™ and “Cold-Metal Transfer” (CMT)

COMELD™ is a recent hybrid joining technology developed by the TWI for CFRP/metal joints, based on the Surfi-Sculpt® surface treatment that aims to combine mechanical interlocking with adhesive bonding [18,19].

Prior to laying up the composite fabrics, an electron beam locally melts the surface of the metal substrate and displaces it to sculpt an array of protrusions. The main advantages of this process in relation to other additive processes, such as additive layer manufacturing or direct metal deposition, is that it does not require complicated extra feed systems of wire or powder [20]. The sculpted metal surface features or “proggles” are usually designed to lean in the opposite direction to the applied load [21] and can be shaped into different geometries and patterns including: single protrusions (Fig. 3 a)), wall features and conical features (Fig. 3 b)) of up to 3.2 mm depending on the actual loading case. Bonding of the texturized metals to composite laminates forms a COMELD™ joint (Fig. 3 c)).

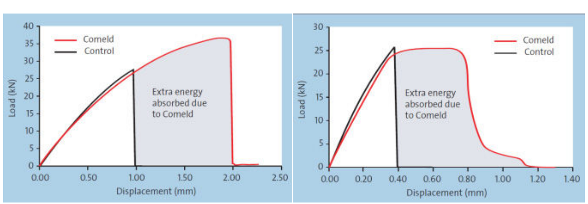


a) b) c)

Fig. 3. a) Typical optimised single protrusion produced in Ti-6Al-4V, b) Conical feature produced in nickel alloy 718 [20] and c) Illustration of a COMELD™ joint [2].

Although being a relatively recent technology, investigations have already been performed to assess

the enhanced static performance of Titanium to CFRP and stainless steel to GFRP COMELD™ joints with respect to *control* joints made by pure adhesive bonding [2,22]. As it can be seen in Fig. 4, the energy absorbed by the COMELD™ joints is around 4 times greater for the Ti-CFRP COMELD™ joints and more than double for the St-GFRP COMELD™ joints than the energy absorbed by the correspondent *control* joints [2]. The additional area under the plots of Fig. 4 arises due to damage induced in the metal and composite before failure, which in the case of both control joints was inexistent. In the case of the COMELD™ joints, initial interfacial failure does not lead to failure of the specimen [21]. Damage of the composite due to matrix cracking accompanied by deformation of the metal "proggles" can be detected before shear failure of the composite in the ST-GFRP joints. In the case of the Ti-CFRP COMELD™ joints, failure can eventually occur due to metal failure [2].
Studies performed to assess an optimal protrusion geometry showed that the angle and height of protrusions are the main parameters affecting the static performance of these joints [18,21]. It seems that the optimised angle of the protrusion lies between 20 and 30° in the opposite direction to the applied load and higher protrusions are more likely to prevent joint failure. It was also revealed that the hill shape is the most favourable protrusion shape since it is the one presenting less stress concentrations.



a) b)

Fig. 4. Load-displacement curves of COMELD™ and adhesive joints [2]: a) St/GFRP joints and b) Ti/CFRP joints.

Another similar technique was also recently developed by the Fronious Company. The "cold-metal transfer" (CMT), first developed for welding of thin aluminium sheets [23], is the basis for producing a high strength and damage tolerant joint between metals and composite parts.
The difference between this and the previously mentioned technique is that, instead of melting the metal substrate itself to shape the spikes, a filler wire with a certain height is melted onto the surface of the metal substrate with the application of a high-current short circuit. These pieces of welding wire- pins- remain attached to the metal acting as "mini-rivets". The most common shapes for the welded pins are the ball-head, cylindrical and spiked pins.

CMT is a fast and automated technique to introduce small metal reinforcements on metal structures [19]. However, subsequent stacking of dry laminate layers on top of the aligned pins is still a lengthy process that needs to be improved. The investigations performed so far to assess the performance of this technology when applied to a stainless steel-CFRP joints revealed that with the ball-headed pins it is possible to obtain an increase in ultimate force of around 53%, 10 times more local strains and 30 times more of energy absorption capacity when compared with conventional adhesive bonded joints. The results were not as impressive for the cylinder and spiked pin reinforced joints, but still interesting. Furthermore, the elasto-plastic behaviour detected in pinned reinforced joints enables continuous and detectable failure behaviour, with minor damages growing until a certain extent that can be detected via visual inspection, before losing structural integrity (Fig. 5).

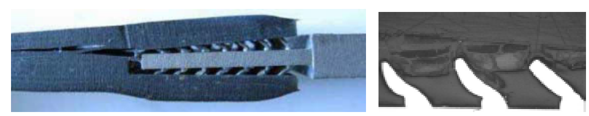


Fig. 5. Stainless steel- CFRP DLS cylinder pin joint [19].

3.2. HYPER

HYPER (HYbrid PEnetrative Reinforcement) is a novel type of hybrid joining method also for reinforcement of CFRP/Metal joints that is under investigation by the AIRBUS Group UK since 2007. Like the previously mentioned techniques, consists in producing a hybrid joint by co-curing a composite and a metal part containing an array of features (HYPINS) protruding from its surface. The difference in this case is that HYPER uses the Additive Layer Manufacturing (ALM) technology to enable cost effective manufacture of the complex features (Fig. 6).

a) b)

Fig. 6. a) An array of additively manufactured titanium HYPER pins [24] and b) HYPIN typical design.

The main advantages of this technology are that no material is wasted during manufacture and almost no constrains exists regarding the pin's geometry [6]. Although this technology is still at a low level of maturity, investigations to date have shown impressive results over unpinned counterparts and other technologies. This is probably due to the unique complex pin shape that can only be produced through ALM technology (Fig. 6 b)) [25]. Under shear loading, the tests performed so far showed an increase of 300% and 128% in ultimate load when compared with bolted and bonded joints, respectively. The mean elongation at maximum load can be increased by over 400% and the energy absorbed can be more than 80 times higher, when HYPIN reinforcements are present [24]. Also significant improvements of up to 6.5 times were revealed in terms of shear strength. Failure mode in single lap shear occurs by shear failure at the base of the metallic HYPINS. In terms of pull-off strength and ultimate force, bolted joints and HYPER joints reveal an equivalent performance with the failure mode being dependent upon the feature geometry and array density. Progressive failure verified for both tests with visible damage of the joint ensures the main purpose of producing an extremely ductile and damage tolerant joint. Preliminary investigations also showed feasibility for implementation of a suitable ultrasonic NDT method for damage inspection [25], no corrosion issues, good fatigue performance [26] and that, when subjected to lightning strikes, HYPINS do not incur in a safety issue.

3.3. RHEA (Redundant High Efficiency Assembly)

The aforementioned novel reinforcement technologies are intrinsically only suitable for metal/composite joints; they imply the existence of a relatively thick metal part from which the pins are sculpted and shaped. This means that none of those techniques are appropriated for reinforcing CFRP/CFRP joints. Thus, a novel hybrid technology for such joints is being developed by the AIRBUS Group, where a low thickness sheet of titanium or stainless steel (0.2 to 0.4 mm) with bent spiked elements (pins) is placed between the two CFRP adherents before or during the co-bonding process, forming a RHEA joint (Fig. 7) [1].

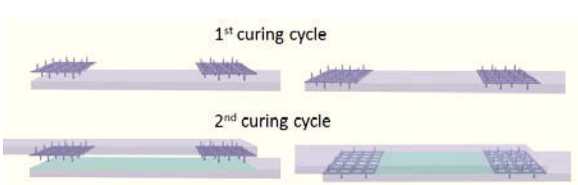
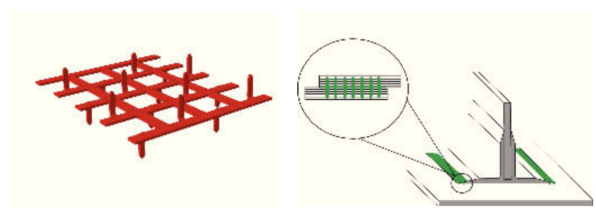


Fig. 7. Manufacture steps of a RHEA joint [6].

Production of these multidimensional metallic reinforcement sheets takes place in one single integrated tooling developed by Hölzel Stans- und Feinwerktechnik GmbH+Co.KG where the spike's contour is firstly stamped and then bent, enabling huge cost and time savings in relation to other technologies. Stainless steel (SAE 304/1.304) and Titanium 15-3 meta-stable-alloy are the preferred metals used for manufacturing the metallic reinforcements since they offer good cold formability (necessary for the sheet metal forming process), high strength and do not bring up issues of galvanic corrosion [6]. Unlike carbon fibre (CF) pins used with the z-pinning technology and others, the continuous metallic pin carrying structure of this sheet bending technology allows to take additional advantage from the increased surface by pre-treating it and in this way enabling further mechanical interlocking with the surrounding epoxy resin and adhesive (Fig. 8) [27]. Moreover, the plastic deformation of these metallic reinforcement inserts allows an additional level of energy absorption in relation to the CF z-pins in which the fracture mechanisms are mostly elastic.



a) b)

Fig. 8. Illustration of: a) metallic reinforcements with bent spikes and b) RHEA T-joint [6].

This technology has proved to be remarkably efficient at increasing shear strength and maximum elongation (up to 118%) for SLS specimens depending on the sheet parameters (sheet thickness, pin density and distribution) [4]. More important, fracture toughness improvements of up to 100% under Mode I and 75% under Mode II loading conditions were encountered in CFRP joints reinforced with this technology [27,28]. This gain in interfacial strength between metallic reinforcements and CFRP adherent is also a result from the surface pre-treatment of the metallic sheets. A novel physical surface treatment of Titanium sheets (α+β-alloy) stands out by modifying its surface to an open-porous nano-roughness scale with the aid of laser irradiation and in this way creating an additional level of mechanical interlocking [28,29].

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