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Enhanced tensile strength of composite joints by using staple-like pins: Working principles and experimental validation

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ABSTRACT

In this study, z-pinning by implementing staples as load-bearing elements for CFRP double-lap joints is presented. Both conventional staples and purpose-made stainless steel wire staples were used as fastener elements. Two different inserting methods were investigated. In addition, the influence of the element's diameter was examined. An overall increase of 28% in tensile strength was determined for stand-alone staples in comparison to bolted joints. A patented principle of edge-staple showed an increase of 23% tensile strength in comparison to purely bonded joints. The geometrical form of staples provides an effective way in terms of axial fixation, since pull out did not occur. Furthermore, the staple principle provides the opportunity to use the elements as supporting entities for bonded joints by reducing peak stresses and suppressing peel. Nevertheless, the test results showed a decrease of the in-plane strength with increasing number of elements, which should be considered for joint design. The study represents a first step in technology evaluation and demonstrates the potential of stapled joints.

1. Introduction

Due to their superior weight to strength ratio, composite materials are increasingly used in aircraft primary structures. This tendency becomes evident with the composite usage for Boeing's 787 and Airbus' A350XWB exceeding 50%. Although, composite technology offers advantages of reducing the need of structural coupling as a result of integral design and special manufacturing techniques, composite structures still show interconnections due to size, design, technological and logistic limitations as well as repair, maintenance and handling requirements [1,2]. Hence, implementing more CFRP load-bearing parts to achieve competitive lightweight structures demands efficient solutions in terms of joining technology. Bonded joints have mechanical advantages since fibers are not cut and stress is transmitted more homogenously than in bolted joints. However, the strength and durability of bonded joints is strongly depended on various factors like surface preparation, joint-end configuration, fiber angles, overlap length, process parameters and many others [3,4]. Experience with bonded composite joints has been extremely varying, with some working well and others failing after short time in service. The usage of bolt-free bonded joints for primary composite aircraft structures is still a certification issue. So called chicken rivets can be used to take remedial action in bonded joints, but increase the weight and weaken the composite material due to cut fibers.

Small diameter elements such as pins or spikes are a promising approach as a new group of joining technologies for composite parts. So far, most types of small diameter elements for joining composites are applied to reinforce adhesive bonds or to improve impact resistance. Those approaches are discussed briefly below.

1.1. Background of small diameter element approaches

z-Pinning is considered to be a good method to achieve enhanced fracture toughness for bonded composite joints. The elements are implemented in the uncured composite which makes z-pinning an additional step in the manufacturing process. Numerous experimental studies by Mouritz et al. [5] confirmed the superior fracture toughness of z-pinned bonded joints for both, mode I and mode II load cases [6–8]. The through-thickness reinforcement by the use of small diameter elements (e.g. Aztex Inc. z-fibers® [6]) bridges cracks, thereby suppresses crack propagation and raises the joint's ultimate strength. If a crack within the bondline reaches the area containing z-fibers, the rods working as bridging entities reduce the magnitude of mode I stresses at the crack's tip and thus delay delamination extension [9]. Since the pins establish a mechanical link between different plies, this reinforcement method can be applied to increase the damage tolerance not only for joints but for the composite itself. However, the short rods have a limited value in damage tolerance, since they get pulled-out at relatively low loads [8] due to the lack of axial fixation. The schematic principle of reinforcing z-pins in bonded joints is shown in Fig. 1.

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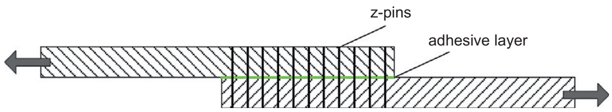

Fig. 1. Schematic principle of z-pins as reinforcing elements in bonded joints.

Another approach to implement small diameter elements as a joining reinforcement is the RHEA concept (Redundant High Efficiency Assembly) developed by Nogueira et al. [10]. The RHEA reinforcement uses spiked metal sheets placed within the bondline in order to gain mechanical load transfer in case of adhesive failure in co-bonded structures. The reinforcement metal sheets are introduced before the laminates curing cycle. Therefore, the working principle is comparable to z-pinning techniques mentioned above.

A third approach working after this crack bridging principle is proposed by Ucsnik et al. [11] using small metal spikes welded onto a metal surface by a technology called cold-metal transfer. A similar principle is proposed by Bettinger [12]. In contrast to the others, these techniques are addressed to reinforce bonded joints between composite and metal.

Stitching (and tufting as well) is another technique of reinforcement perpendicular to the laminate. Heß et al. and Dransfield et al. showed that these techniques enhance the fracture toughness for composites under peel load conditions, too [13,14]. However, a stitching thread cannot carry any shear load.

All these methods increase the strength of bonded joints, but they lack in providing a robust and fail-safe design to overcome the certification issues for bonded joints since element pull-out can occur (with the exception of stitching). Furthermore, all techniques are limited for co-bonded or co-cured structures since the reinforcement entities need to be in place prior to laminate curing in at least one joint part.

1.2. Working principle of load-bearing staples

The DLR investigations are focused on the usage of small diameter pins as stand-alone load-bearing entities and therefore differ to the other approaches mentioned above. Replacing conventional bolts by small diameter elements requires a way of axial fixation. Simple u-shaped wire is considered to be an easy and reliable way to attain fixation in the material's z-direction. These short pieces of u-shaped wire are driven through the surface and clinched on the other side (Fig. 2). This principle is known from conventional staples used to bind papers together. It is the major goal of this study to evaluate the capabilities of this joining concept in terms of joint strength in comparison to conventional bonded or bolted joints.

Replacing conventional fasteners by small diameter elements has certain benefits. Kröber showed that the open-hole stress concentration factor decreases with the hole's diameter for CFRP, independent of the stacking sequence (so called hole size effect) [15]. His calculations are based on the Point-Stress-Criterion introduced by Whitney and Nuismer [16]. Thus, using smaller elements increases the ultimate fracture strength in the joining area, regarding bypass load concentration (Fig. 3b).

However, the stress distribution around the hole differs for loaded hole scenarios. In addition, to stress peaks at the hole's edge (Fig. 3a), there is a considerable stress concentration at the pressure point of loaded holes (Fig. 4), which could lead to bearing or shearing failure at high load levels. The specific stress distribution around a loaded hole is influenced by various factors like material properties, material thickness, stacking sequence, element pitch, element diameter, element clearance, insertion method and many other factors [18,19]. Hence, reliable determination of the load-bearing capacity is normally done by tests. The joint efficiency J of a single row fastened joint is defined as the ratio of the maximum bearing load P_B that is transferred by the bolt to the ultimate tensile load P_{TU} for the unnotched laminate (see Eq. (1)). The joint efficiency J is a function of the laminate tensile strength σ_{TU}, bearing strength σ_B, the width w, the material thickness t and diameter of the bolt d [19].

$$J = \frac{P_B}{P_{TU}} = \frac{\sigma_B \cdot d \cdot t}{\sigma_{TU} \cdot w \cdot t} \tag{1}$$

The joint efficiency of composites is considerably lower than for metals. This problem has been known ever since composites were considered for load-bearing structures. Former studies showed that the failure mode and the joint efficiency are highly driven by the w/d ratio and have an optimum of w/d equals 3.5–5 [20]. A smaller w/d ratio typically leads to net tension failure. Larger w/d ratios shift the failure mode to bearing.

Former experimental studies showed that decreasing the element diameter increases the overall joint strength for static load cases, especially for elements with less than 2 mm in diameter [21,22]. Iliina et al. gained over 90% of overall joint efficiency for single-lap joints with 0.8 mm and 1.0 mm steel pins [21]. Micromechanic effects are assumed to be the main reason for the increasing joint performance. The first and last element in both single and double-lap joints always transmit the maximum loads. Load concentrations at the first and last row of small diameter elements supposedly cause local softening of the material due to delamination, fiber microbuckling and nonelastic material behavior with increasing loads. This local softening effect therefore causes load redistribution and reduces the stress concentration factor near the high-loaded holes [22]. Thus, the overall load is transmitted more equally through all elements, which increases the joint's overall load-bearing capacity. The beneficial load redestribution caused by softing effects could also be achieved by implementing inserts of soft material in the vicinity of loaded holes as shown by Kolesnikov [23].

Furthermore, replacing a certain number of conventional fasteners (e.g. rivets) by a greater number of smaller elements of the same overall shear plane increases the overall available load-bearing area. This relationship can be proven easily by following formulas. The elements transmitted force L is given by [1]:

$$L = i \cdot S \cdot \frac{\pi}{4} \cdot d^2 \tag{2}$$

S is the bolt's shear strength and i the number of bolts. The bearing pressure is given by (3), with t being the material thickness.

$$p_{max} = \frac{L_{max}}{d \cdot t \cdot i} = \frac{S_{max} \cdot \pi}{4 \cdot t} \cdot d \tag{3}$$

These formulas are valid for a single-lap joint under the simplifying assumption that all elements carry loads equally. It becomes evident that the bearing capacity for a constant overall shear area is strongly driven by the element diameter. Since composites have a relatively poor bearing strength compared to metals, small diameter elements clearly improve the bearing strength and therefore improve the joint's performance. However, increasing the number of elements is limited by geometrical boundary conditions. Today's pitch limits for bolted composite joints are designed for conventional fasteners and should be reconsidered for small diameter elements since mechanical effects and stress concentrations may differ compared to conventional fasteners.

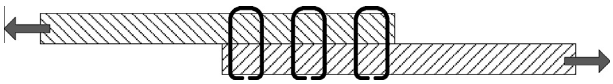

Fig. 2. Schematic principle of staples as load-bearing elements.