Composites: Part A 98 (2017) 192–206

Contents lists available at ScienceDirect

Composites: Part A

journal homepage: www.elsevier.com/locate/compositesa

Loading, support and geometry effects for pin-reinforced hybrid metal-composite joints

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ARTICLE INFO

Article history:
Received 2 November 2016
Received in revised form 18 March 2017
Accepted 21 March 2017

Keywords:
A. Hybrid
C. Finite element analysis (FEA)
D. Failure
E. Joints/joining

ABSTRACT

Reliable joining technologies are increasingly required for multi-material lightweight structures. For metal-composite joints, there is significant potential to integrate through-thickness pins onto the metal surface to improve bond strength. We investigated Selective Laser Melting manufactured Ti-64 adherends with integrated pins bonded to carbon fibre-reinforced polymer composite, and characterised joint performance from pure tension to shear-dominated pin loading. Both single pin and multi-pin double cantilever beam specimens were examined and correlated using experimental and finite element methods. Adherend support conditions affected the single pin pull-out process and related energy absorption up to 35% for all pin offset angles. The pin alignment with respect to the crack direction and fibre angle had little effect on joint performance. Pins with grooved surface features further increased energy absorption by 60% compared to smooth cylindrical pins. This work adds significant insight into pin-reinforced hybrid metal-composite joints and their performance and optimisation in realistic structural scenarios.
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1. Introduction

Hybrid metal-composite joints are becoming more common in many engineering structural applications especially in the aerospace industry due to extensive use of carbon fibre-reinforced polymer (CFRP) composites. One of the latest breakthroughs is the implementation of hybrid titanium-CFRP composite fan blades on modern aero engine models such as GE9X (GE Aviation) and Advance (Rolls Royce), which offer 30% reduction in weight and 20% boost in efficiency/emission reduction [1]. In this system, the composite fan blade is bonded to a titanium leading edge [2] for improved damage tolerance under impact. The mechanical performance of this joint category can be further enhanced with the addition of surface features along the bondline through advanced manufacturing techniques. Recent research by the authors has employed the selective laser melting (SLM) technique to successfully produce functional titanium adherends integrated with hierarchical groove features [3] or through-thickness reinforcement (TTR) pins [4] for joining to CFRP composites.

The behaviour of the pins reinforcing the hybrid joint under tensile (pull-out) loads has been characterised in detail by the authors [4], and established the relation between the pin geometry parameters, pin/composite interface and failure mode, as well as compared findings to similar research for carbon z-pinned composites [5–10]. Separately, the behaviour of a pin-reinforced hybrid joint in pure shear or shear-dominated loading has been investigated by several researchers. Generally, depending on the type of pin, three types of damage modes have been observed, including pin fracture in the case of pins with tip features [11–14], pin deformation accommodating the pull-out in the case of a straight cylindrical pin [14,15], and composite damage in the case of a triangular pin [16]. These published studies show that in both pull-out and shear the strength and damage mode of the pins directly influence the overall damage pattern of any multi-pin joint, where pin fracture and composite (adherend) fracture lead to catastrophic failure while pin bending and pull-out result in a more progressive failure process with higher energy absorption. However, the effect on the pin pull-out process for different combinations of mode mixity has not been characterised, and the variation in pin performance between the limiting cases of pure tension pull-out and shear-dominated loading is not well understood. Further, there have been no studies considering the introduction of pin surface features or alternative pin geometries that can enhance the energy absorption during pull-out, without increasing the pin strength to such an extent that catastrophic adherend fracture occurs.

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http://dx.doi.org/10.1016/j.compositesa.2017.03.019
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In the broader body of knowledge on TTR pins such as carbon z-pin reinforced composites, related knowledge on pin behaviour under varying combination of pull-out and shear loading has been presented in several publications. This is commonly investigated using pull-out of pins that are manufactured at an "offset angle" with respect to the loading axis. Cox et al. [17,18] developed a semi-analytical model for pin traction under varying loading conditions, where the shear loading caused an identified pin "snubbing" effect that was incorporated as an additional friction component in pure pull-out loading. An experimental study by Yasaee et al. [19] on single pin specimens with offset angles indicated that only a limited range of angles produced stable pin pull-out behaviour, i.e. below 11° for pins embedded in a unidirectional laminate or 33° in a quasi-isotropic laminate. Above such values, the pin fracture and energy absorption was similar to when the pin was loaded under pure shear. M'membe et al. [20] and Cartie et al. [5] showed that the maximum load and energy absorption increased with increasing offset angle when the pin was oriented in the direction of the load. In terms of damage mechanisms, the region around the pin cavity was crushed and the pin deformed laterally to accommodate the pin pull-out process [5,21,22]. Despite these insights, no correlation to the ratio of pull-out and shear stresses has been established, and no correlation has been made between single pin pull-out and multi-pin joint performance. Additionally, the range of offset angles (and hence ratio of pull-out and shear stresses) has been relatively small due to the low shear strength of the carbon z-pins, and a much broader characterisation is required for titanium pins in a hybrid joint due to the strong pin-composite bond [4]. Further, the change in joint behaviour depending on how the pin is inclined relative to the composite fibre architecture or the crack growth direction is not well understood, and it is not clear in what circumstances joint behaviour is affected.

Another important aspect of joint performance that is relevant to industrial structures is the support condition of the adherends. This relates to whether the adherends are fixed as the pin is pulled out, or whether the adherends and supporting structure can adjust to the forces generated in the pull-out process. This is particularly critical where the pins have an offset angle, as the additional effects such as snubbing and pin bending cause forces that promote lateral displacement and rotation of the adherends. As such, it is important to characterise the joint performance between the two extreme conditions of adherends that are fixed or relaxed to self-adjust, which has not previously been studied. Understanding the effect of support condition in single pin specimens allows the support condition in multi-pin joints to be identified, which then relates to improved understanding of the corresponding damage modes and joint performance. This also provides critical information regarding the test method that is most appropriate for single pin specimens in order to correctly correlate to multi-pin performance. To the authors' knowledge none of the multi-pin structures previously studied in literature have had an assessment of the adherend support conditions.

In this study, the performance of reinforcements in hybrid SLM metal-CFRP composite joints is investigated in single pin specimens and multi-pin joints. Single pin specimens of varying pin geometry (length, diameter, offset angle and features) and adherend support condition (fixed and relaxed to self-adjust) are used to characterise the composite microstructure and the response of the single pin as it is pulled out of the composite under different loading combinations. Our previous publication [4] used a similar investigation method to successfully characterise the pin/composite interface strength and to determine the critical L/D aspect ratio of the pin to achieve complete pull-out for straight pins. This study further focuses on varying the pin offset angle (to control the ratio of pull-out to shear stresses), adherend constraint, pin orientation with respect to the load direction and fibre direction, and surface features of the pin. Double Cantilever Beam (DCB) specimens in unpinned and pinned configurations are tested experimentally and analysed with finite element (FE) models. This work characterises in detail the influence of the aforementioned joint parameters on the pull-out performance of single-pin specimen, and the findings are furthermore correlated with properties of multi-pin joint configurations. The use of single-pin and multi-pin joints in the same study also provides a key understanding of the correlation between these joint types with regards to the damage modes, joint performance and adherend constraint. The characterisation across different pin geometries (pin diameter and length) and surface features deepens our understanding of energy absorbing features at different length scales.

2. Experimental methodology

2.1. Single pin pull-out test

The additive manufacture in form of selective laser melting (SLM) was utilised to print components from Ti-64 in a build chamber of 250 mm × 250 mm × 350 mm (SLM250HL, SLM Solutions, Germany). Prior to printing, the chamber was filled with Argon gas to avoid oxidation of the component during the manufacturing process. The platform was pre-heated to 200 °C to minimise build-up of residual stresses during manufacturing. The adherends were printed with a layer thickness of 30 μm using a YLR-Fibre-Laser at 175 W. The process parameters are listed in Table 1. A porosity content of 0.3% ± 0.1% was obtained during the printing process (3D X-ray Computer Tomography) with an average surface roughness (S_a) of 10 μm ± 3 μm (Alicona IF-EdgeMaster profilometer). Single pin specimens were printed on a square platform with a centre pin positioned at various offset angles ranging from 0 to 30° (Fig. 1a). The overall dimensional tolerance of the SLM-manufactured components was very high, with an average tolerance of 0.1 mm for all pin dimensions. The titanium adherend thickness was accurate within 0.05 mm. The composite adherends were manufactured from T700 carbon/epoxy pre-preg tape (VTM264, Advanced Composites Group) with unidirectional lay-up for best match with the titanium arm stiffness. The hybrid joints were autoclave co-cured according to manufacturer recommendations for the composite (120 °C, 620 kPa, 1 h). A polytetrafluoroethylene (PTFE) film of 0.1 mm thickness was inserted at the interface of the titanium adherend and the composite to act as a starter crack (see Fig. 1a). This allowed measurement of the pull-out response of the pin, as the adhesion properties between the two materials were characterised previously [4]. In addition, the PTFE film thickness does not affect the overall pull-out results as the film thickness is significantly smaller than total interface area between the pin and the composite.

Following curing, aluminium tabs were adhesively bonded to the surface of the adherends using a thinly spread layer of commercial (420A) Araldite adhesive with room temperature cure. As the tip of the pin is chamfered, there was no contact between the pin and the applied adhesive. Two types of test setup, a fixed constraint and a self-aligning or "relaxed" constraint, were developed to apply the tensile loading (see Fig. 1b). In the self-aligning setup, the tabs were connected to a double lap joint with a single bolt on each side of the joint, and the other side of the joint was clamped in the machine grips. This allowed for relative horizontal movement (along x-axis) of the two adherends to self-adjust or re-orient during the pin pull-out process as the joints are loosely bolted. In the fixed setup, the tabs were simply gripped in the test machine and the adherends had no freedom to self-adjust.

Seventeen different specimen configurations for single pin pull-out were investigated as shown in Table 2. The pins in all

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