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Comparative study of metal and composite z-pins for delamination fracture and fatigue strengthening of composites

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ABSTRACT

The influence of the material properties of z-pins on the mode I delamination properties of carbon–epoxy laminates is investigated. Improvements to the delamination fracture toughness and fatigue resistance of laminates reinforced in the through-thickness direction with z-pins made of metal (copper, titanium or stainless steel) or unidirectional carbon fibre composite is determined. Irrespective of the material, the z-pins are highly effective at increasing the fracture toughness and fatigue resistance by forming a large-scale bridging zone along delamination cracks. However, the fracture toughening and fatigue strengthening capacity of the z-pins is strongly dependent on their material properties, and increased in the order: copper (least effective), titanium, stainless steel and carbon fibre (most effective). The fracture and fatigue failure modes of the z-pins are also dependent on their material properties. The study reveals that improvements to the mode I fracture toughness and fatigue resistance can be optimized via a judicious choice of the z-pin material. Z-pins with high stiffness, strength and fatigue resistance (such as carbon fibre) provide the greatest improvement to the delamination toughness and fatigue strength.

1. Introduction

A long-standing concern with using brittle matrix polymer composites in aircraft structures such as carbon fibre reinforced epoxy laminate is delamination cracking. Delamination damage to composite aircraft structures may be caused by extreme through-thickness (interlaminar) static and fatigue loads, edge stresses, environmental degradation, or an impact load (e.g. hail stone, bird strike). Delamination cracks can reduce the in-plane mechanical properties and create pathways for the accelerated ingress of water and other fluids, which can further reduce the properties.

One well-established technique to improve the delamination resistance of laminates is z-pinning. Z-pins are thin metal or fibrous rods that are inserted through-the-thickness of the uncured composite during fabrication [1–3]. Many experimental and numerical studies have proven that z-pins can increase the delamination fracture toughness and delamination fatigue resistance of brittle polymer matrix laminates, as reviewed in [1]. Improvements to the delamination fracture and fatigue properties are controlled by the volume content [4–13], diameter [6,7,10] and embedded length [13,14] of the z-pins. Due to the increased delamination toughness, the impact damage resistance, post-impact mechanical properties and damage

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Nomenclature

a	total crack length
a_o	length of pre-crack tip
Δa	change in crack length
b	width of the DCB specimen
C	fatigue material constant
d_p	z-pin diameter
da/dN	fatigue crack growth rate
G_{Ic}	mode I fracture toughness
ΔG_I	mode I cyclic intensity
l_p	z-pin length
m	fatigue material exponent constant
P	applied force
P_p	z-pin traction force
δ	crack opening displacement
$\lvert\Delta l\rvert$	correction factor
τ	interfacial shear failure stress between z-pin and laminate

Table 1
Composition of z-pins. Values are average weight percentage.

Z-pin	Composition
Copper	<0.1% trace elements, balance Cu (99.9%)
Titanium (Grade 1)	0.08% C, 0.2% Fe, 0.013% H, 0.05% N, 0.1% O, balance Ti (99.5%)
Stainless steel (316L)	0.03% C, 2.0% C, 0.75% Si, 17% Cr, 12% Ni, 2.5% Mo, 0.045% P, balance Fe
Carbon fibre	T650 carbon fibre, bismaleimide matrix

tolerance of laminates are improved with z-pins [1]. Similarly, the ultimate failure load and fatigue life of bonded composite joints can be increased with z-pins [1].

The majority of studies have focussed on z-pins made of unidirectional carbon fibre rods, and much less is known about the efficacy of metal z-pins. Rugg et al. [15] found that titanium z-pins are highly effective at increasing the delamination toughness of carbon–epoxy laminates and the ultimate strength of T-shaped bonded composite joints under mixed-mode interlaminar loading. Cartié et al. [16] determined the mode I and mode II crack bridging traction properties of titanium z-pins inclined at different angles within carbon–epoxy laminate, and measured a large delamination toughening effect. Son et al. [17] recently reported that stainless steel z-pins increase the ultimate and fatigue strengths of composite lap joints under room temperature, hot/dry and hot/wet environmental conditions. Despite these studies, the capacity of metal z-pins compared to the more studied carbon fibre z-pins to improve the delamination resistance of laminates under static and fatigue interlaminar loads is not well understood. Also, the delamination toughening gained by metal z-pins has only been studied for titanium alloy, and the capacity of other types of metal z-pins to promote high toughness and fatigue strength is not known.

A comparative study is presented into the efficacy of z-pins made of carbon fibre or metal to improve the mode I fracture toughness and fatigue strength of an aerospace-grade carbon–epoxy laminate. The carbon fibre z-pins were made of unidirectional graphite fibre–bismaleimide rods and the metal z-pins were made of copper, stainless steel or titanium rods. The capacity of the different z-pin materials to increase the mode I interlaminar fracture toughness and alter the delamination toughening mechanism is experimentally determined. In addition, the improvement to the mode I delamination fatigue resistance and the fatigue strengthening mechanisms due to the carbon fibre and metal z-pins is assessed. The research presented in this paper highlights the importance of the material properties of the z-pins in promoting high delamination toughness and fatigue resistance in laminates.

2. Materials and experimental methodology

2.1. Composite materials

Z-pinned laminates were made using unidirectional T700 carbon fibre–epoxy prepreg tape (VTM264 supplied by Advanced Composites) with a ply stacking sequence of $[0_6[90/0]_2]_s$. The uncured prepreg was debulked following the