SUPPRESSING DELAMINATIONS IN COMPOSITES ACROSS A RANGE OF LOADING MODES

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ABSTRACT

This study presents two means of achieving high fracture toughness throughout the entire mixed Mode I/II test range, using customised placement of composite and metal Z-pins in *hybrid arrays*, and novel *hybrid metal/composite Z-pins*. The study shows that hybrid arrays that contain an equal number of composite and metal Z-pins exhibit a notable increase in the apparent fracture toughness in Mode II compared to 100% composite pins, while maintaining adequate Mode I performance. Hybrid metal/composite Z-pins, which consist of a composite exterior and a metal core have been shown to offer a single Z-pin solution for high fracture toughness under mixed Mode I/II loads without compromising either Mode I or Mode II performance of individual composite or metal Z-pins respectively. The composite exterior of the hybrid Z-pin ensures high resistance to pull-out failure, whilst the metal core guarantees high energy absorption at high mixed mode load angles via plastic deformation.

1 INTRODUCTION

Localised through-thickness reinforcements (TTR), such as tufting, stitching and Z-pinning, are recently developed approaches used to increase the delamination resistance of continuous fibre reinforced polymer matrix composites. Amongst these, Z-pinning is the technique best suited to localized reinforcement of structures laid up from prepreg materials. The best known composite Z-pins are manufactured from pultruded carbon fibre/bismaleimide impregnated tows. Less often, metallic Z-pins such as copper, stainless steel and titanium are also used [1–4]. The main drawback with using metallic Z-pins is poor bonding of the Z-pins to the laminate which causes relatively poor Mode I apparent fracture toughness. Thus surface treatment of metallic Z-pins is required to ensure high frictional energy dissipation under Mode I dominated loads [1–4]. Metallic Z-pins also have a higher mass density compared to composite Z-pins. In contrast, composite Z-pins are light-weight and have good interfacial bonding with laminates, which can result in improvements to the resistance of Mode I delaminations by factors in up to 20 times compared to the control [5].

The bridging behaviour of carbon fibre Z-pins under mixed Mode I/II loading was characterized by Yasaee et. al. [6]. Composite Z-pins provide high apparent fracture toughness at low Mode I/II mixities where the pull-out failure mode is dominant. However, at high shear dominated mode mixity ratios, Z-pin rupture (transverse failure of the pins) dominates and hence lower apparent fracture toughness is noted. In contrast, metallic Z-pins inserted into the same laminate are able to absorb large quantities of energy under Mode II dominated load by undergoing extensive plastic deformation [3][7]. However, in Mode I, weak interfacial bonding with composites means that surface treatments through organosilane-coupling agents [3] or mechanical roughening [2], are an essential additional step during manufacture.

With surface treatments, metallic Z-pins can perform just as well as composite Z-pins under Mode I loading [3][7].

This study presents two means of ensuring enhanced apparent fracture toughness of Z-pinned composites, across the full range of Mode I/II load angles, by developing novel Z-pin solutions that incorporate both metallic and composite material features. The first of these solutions is the use of *hybrid Z-pin arrays* that contain a fixed ratio of metal to composite Z-pins. The second solution proposed is a *hybrid Z-pin*, which consists of a metal core encased in a composite exterior. The composite exterior of the Z-pin ensures high interfacial properties with the surrounding laminate and consequently high apparent fracture toughness at low mode mixities. The metallic core of the hybrid Z-pin increases the transverse stiffness and ductility, which results in increased apparent fracture toughness at high mode mixities, where bending and shear failure are dominant.

2 MATERIALS AND METHODS

Quasi-isotropic composite laminates were reinforced with metal and composite Z-pins to make 20 x 20 x 8 mm specimens. The laminates were made from carbon/epoxy IM7/8552 prepreg tape, supplied by Hexcel. The specimens had a $[0,+45,90,-45]_{4s}$ layup in the top half and a $[90,-45, 0,+45]_{4s}$ layup in the bottom half, separated by a layer of PTFE film as shown in Figure 1. The single pin specimens were tested at a range of mixed mode angles on an Instron 8872 universal testing machine with a 1kN load cell at a rate of 0.5 mm/min until failure. A full description of the experimental procedure is given by Yasaee et al. [6] and M'membe et al. [8].

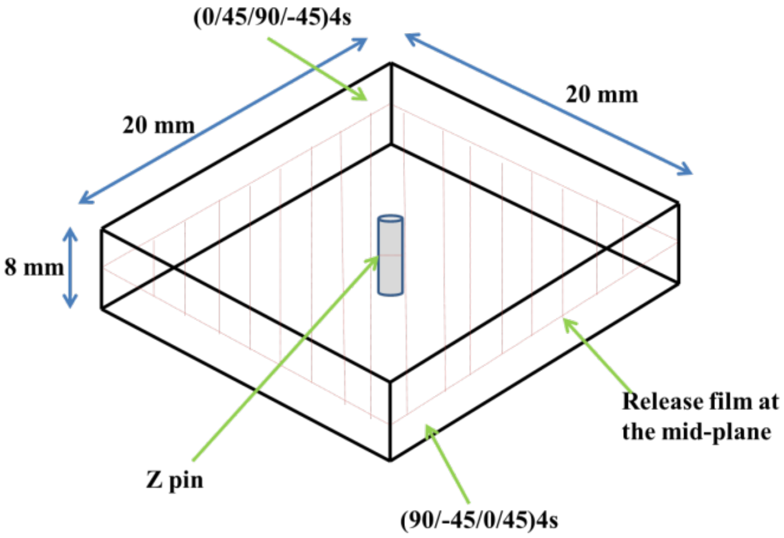
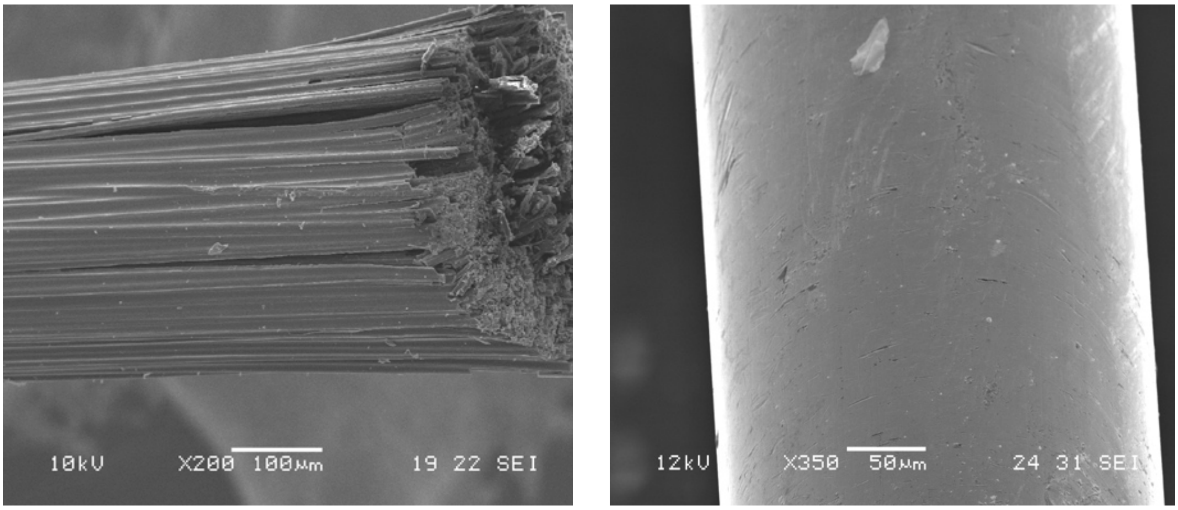


Figure 1: Schematic diagram of single Z-pin specimens

The composite Z-pins used in this study were made from T300/Bismaleimide (BMI) carbon fibre rods. The Z-pins had a nominal diameter of 0.281mm. The metallic Z-pins were made from a high corrosion resistant austenitic stainless steel (304) used for non-invasive medical procedures. They had a nominal diameter of 0.3mm. Figure 2 shows the surface morphologies of these Z-pins.



T300/BMI carbon fibre Z-pin **Stainless steel Z-pin**

Figure 2: Micrographs of the surfaces of the composite and metal Z-pins used in this study

Figure 3 shows the modified forms of the single pin test specimens used to characterize the bridging behaviour of hybrid arrays using T300/BMI and stainless steel Z-pins. Two types of hybrid arrays were tested: 4 pins and 16 pin arrays. The metal and composite Z-pins in each array were uniformly mixed i.e. each composite Z-pin was adjacent to metal Z-pin in the horizontal and vertical directions in the array. The 16 pin arrays specimens were reinforced with different percentages of composite Z-pins, that is 100%, 75%, 50%, 25%, as well as 100% metal. The four pin arrays had an equal number of composite and metallic Z-pins (i.e. 50%).

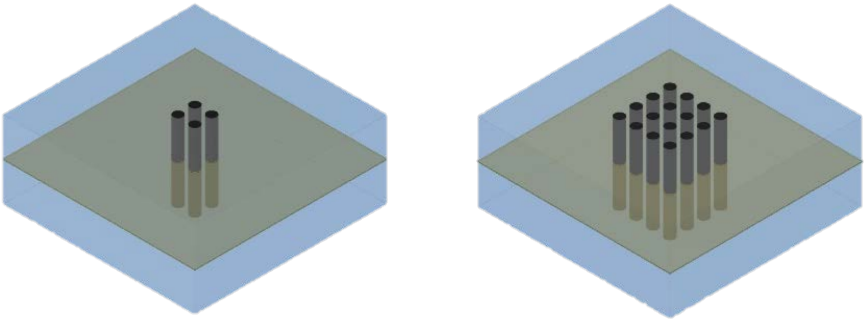
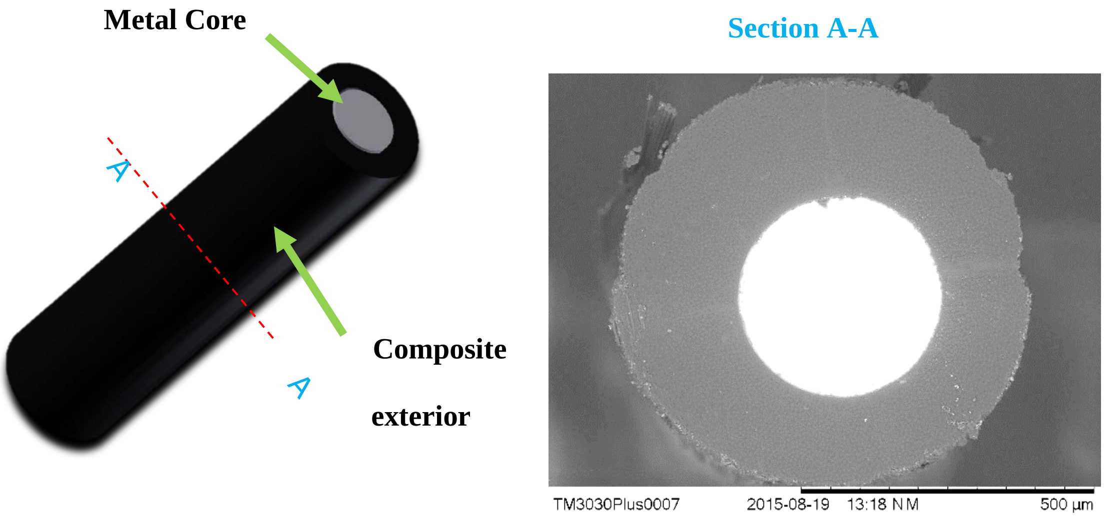


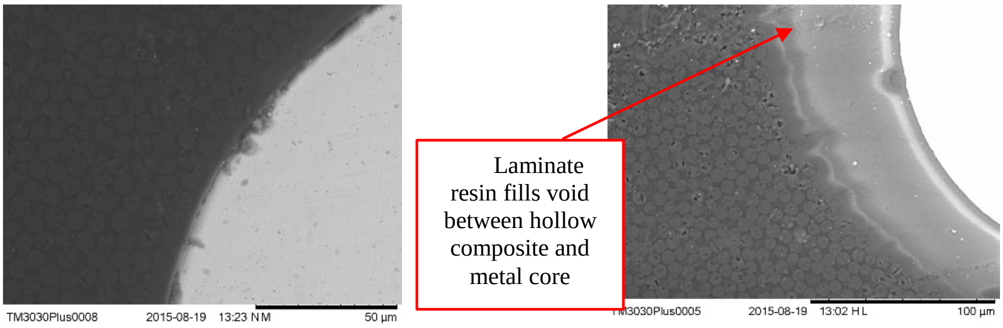
Figure 3: Hybrid array test specimens, with 4 and 16 pins

On an industrial level, the novel *hybrid metal/composite Z-pin* can be realised by braiding composite fibres over a metallic core. However, in this study, hybrid Z-pins were created by inserting circular metal rods into the core of hollow pultruded carbon fibre rods as shown in Figure 4. The circular hollow fibres, which had an external diameter of 700 µm and an internal diameter of 400µm, were made from T300 carbon fibre tow impregnated with epoxy. They were supplied by vDijk Pultrusion Products (DPP). The metallic core materials used were Titanium alloy (400µm diameter) and stainless steel (300µm diameter) i.e. metal A and metal B respectively. While metal A had a flush fitting with the exterior composite core, the metal B pins were loosely fitted, resulting in the laminate matrix filling in the void space as shown in Figure 5. The test results were compared to circular solid Z-pins with a diameter of 700µm manufactured from the same pultruded carbon-fibre material as the hollow composite exterior.



(a) (b)

Figure 4: Hybrid composite pin (a) schematic diagram and (b) SEM of a hybrid test specimens cross sectional area (Metal A core)



Metal A Metal B

Figure 5: Micrographs of the cross section of hybrid Z-pins with flush fitting and loose fitting

3 RESULTS AND DISCUSSION

3.4 Hybrid arrays

Figure 6 and Figure 7 show representative load-displacement plots for 16 pin hybrid array specimens tested in Mode I and Mode II respectively. In general, composite and metal Z-pins are best suited to low and high mode mixity load cases respectively. Therefore the results show that in Mode I, there is gradual increase in maximum load and therefore frictional energy dissipated, as the content of carbon Z-pins increases in the specimens. Similarly in Mode II, the energy absorption increases as the content of stainless steel Z-pins increases. Thus, a hybrid array with an *equal* combination of metallic and composite Z-pins ensures that a Z-pinned laminate will display high apparent fracture toughness throughout the mode-mixity range.

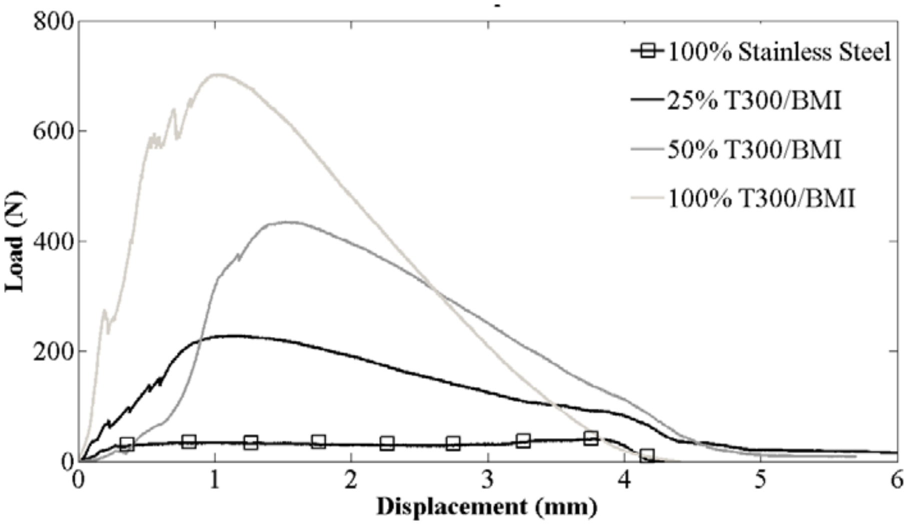


Figure 6: Load displacement plots of 16 pin hybrid arrays in Mode I

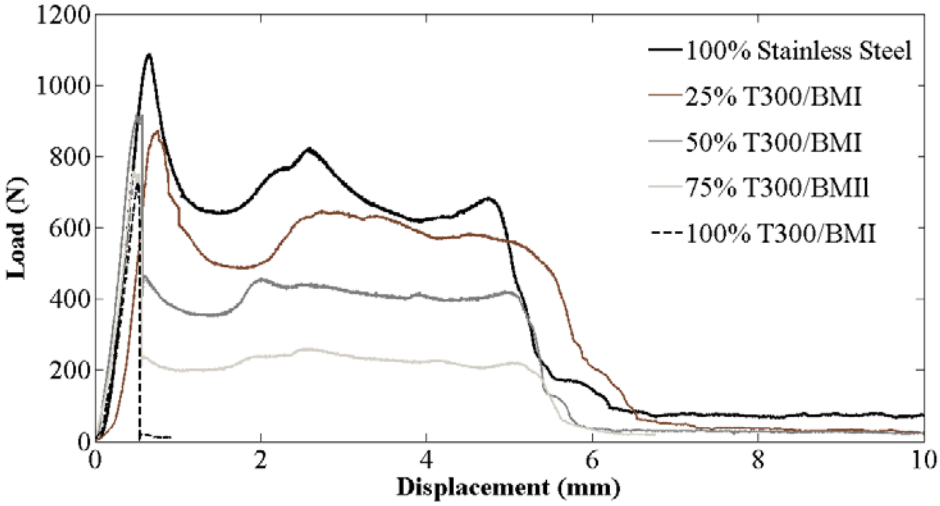
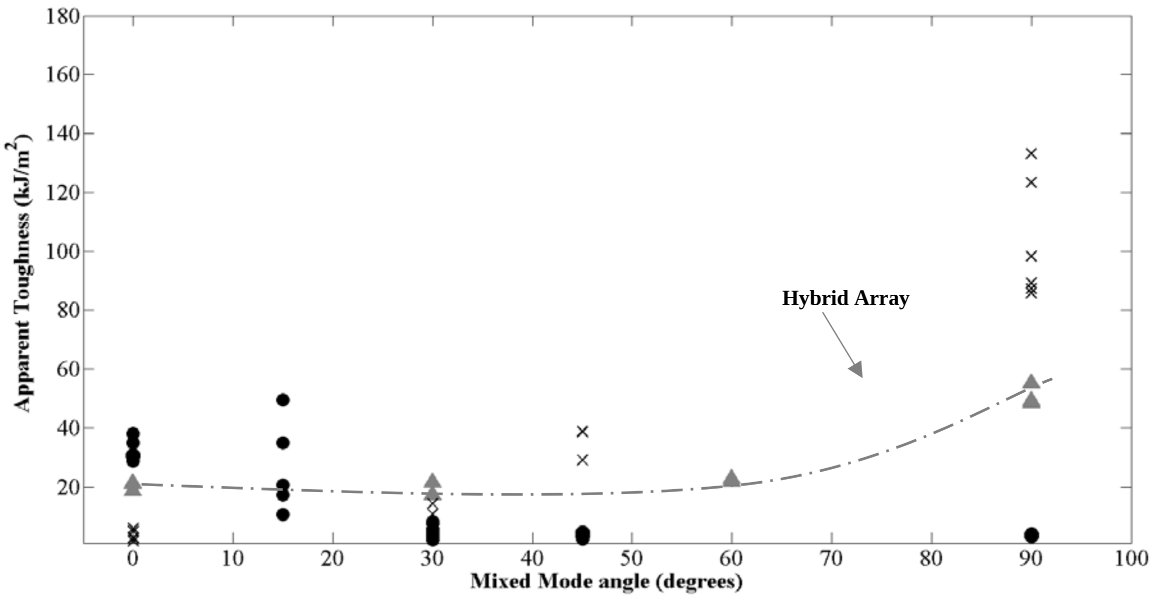


Figure 7: Load displacement plots of 16 pin hybrid arrays in Mode II

Figure 8 shows the apparent fracture toughness based on 2% areal density of several combinations of hybrid arrays in a quasi-isotropic carbon fibre reinforced composite. The hybrid arrangement of both composite and metal Z-pins shows a significant increase in the fibre bridging capacity in Mode II, compared to 100% composite pins, while maintaining adequate Mode I performance. The result is *almost* constant apparent fracture toughness for mixed mode angles up to 60 degrees, which can lead to significant simplifications in the design process of Z-pinned composites. The use of metallic Z-pins with better adhesion with the laminate would help to mitigate the loss in Mode I energy absorption. Hybrid arrays therefore offer a readily available solution to Z-pin arrays subjected to mixed Mode loads.

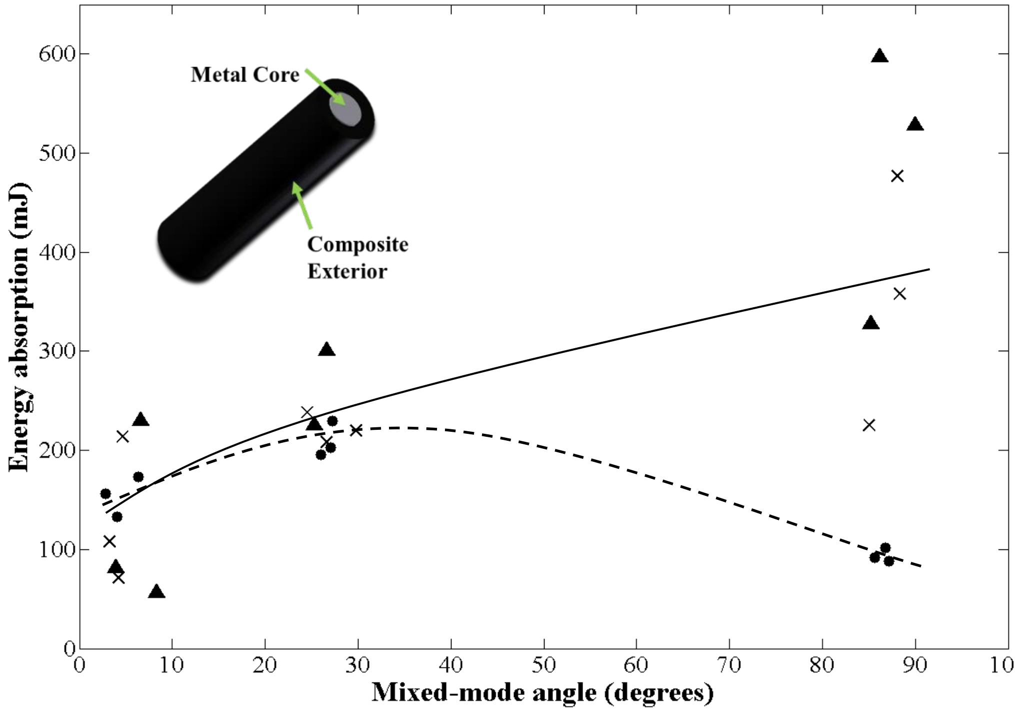


	100% composite	50% composite	100% metal
specimen	●	▲	x

Figure 8: Comparison of apparent fracture toughness (normalised for 2% areal density) between 50% metal-composite Z pin arrays, composite only Z-pin arrays and metal only arrays.

3.5 Hybrid Z-pins

Figure 9 shows the energy absorption/dissipation of the hybrid Z-pins compared to composite Z-pins. Composite Z-pins have relatively high apparent fracture toughness at low mixed mode angles where frictional pull-out of the Z-pins is the dominant failure mode. While the transition to fracture failure occurs at lower mode mixities for the 0.281 diameter Z-pins [6][8], the larger 0.7mm diameter Z-pins are able to resist the shear forces more effectively; hence pull-out is maintained even at 30 degrees mixed mode angle. Thus, larger composite Z-pins are recommended in cases where a larger pull-out region in the mode-mixity domain is required – on condition that the in-plane properties and effective surface area of the TTR are not significantly reduced relative to 0.281mm diameter Z-pins.



	100% composite	Hybrid-Metal A	Hybrid-Metal B
specimen	●	▲	x

Figure 9: Comparison of metal-composite Z hybrid pins to composite only Z-pins. *Solid line fits hybrid pins and dotted line fits composite pins.*

At the low mixed mode angles tested in this study, there are no significant differences between the hybrid Z-pins and the composite Z-pins within the limits of the scatter in the results. The composite exterior in the hybrid Z-pins ensures good bonding occurs between the Z-pin and the laminate. In both cases, the energy dissipation of the Z-pins increases at 30 degrees mixed mode angle due to snubbing effects from the surrounding laminate. At higher mixed mode angles, the energy absorption of the hybrid Z-pins increases due to the presence of the metallic core, which allows for pull-out failure. The composite Z-pins fail via rupture, which leads to lower apparent fracture toughness. The hybrid Z-pins used in this study are significantly larger than conventional Z-pins. Further studies will need to be carried out for hybrid Z-pins with smaller diameters.

4 CONCLUSIONS

In this study, *hybrid arrays* combining metallic and composite Z-pins, and novel *hybrid metal/composite Z-pins* have been proposed. The solutions put forward are applicable to structures loaded with high and low mode mixities during service. Unlike the options presented in the literature, *hybrid arrays* and *hybrid Z-pins* do not require additional surface treatments to ensure relatively high apparent fracture toughness throughout the Mode I/II range.

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