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Mode II delamination resistance of composites reinforced with inclined Z-pins

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ABSTRACT

Z-pin reinforcements in composite materials significantly enhance the through-thickness strength by providing strong bridging forces on the delaminated surfaces of a damaged laminate. The bridging forces have been shown to be more effective in mode I dominated delamination cracks than in mode II shear dominated cracks. One solution to help improve the Mode II delamination resistance of Z-pins is to incline the pins such that the angle between the longitudinal axis of the pin and the shear force load vector is reduced. In this study, the Mode II resistance of laminated composite reinforced through the thickness with inclined Z-pins is characterised. There is a notable increase in the apparent fracture toughness of composites when Z-pins are better aligned with the shear load vector (inclined) compared to the conventional, orthogonally inserted Z-pins. Brittle, catastrophic failure however occurs when the inclined Z-pins are angled against the shear load vector. For many structures the direction of the local direction of shear load cannot always be predicted, therefore a general approach for inclined Z-pins using a $\pm \theta$ configuration was also investigated. With this setup, a modest improvement in the apparent fracture toughness was obtained.

1. Introduction

Laminated composite materials lack through-thickness reinforcements (TTR), which often leads to their failure through delamination. Depending on the manufacturing process, that is resin infusion or prepreg, TTR techniques such as tufting, stitching, Z-anchoring and Z-pinning have been used to improve the interlaminar strength of composites by suppressing delamination growth. Normally for resin infusion processes, tufting, stitching and Z-anchoring are commonly used. However, attempts to apply these techniques to uncured prepreg results in extreme fibre damage and consequently reductions in the in-plane mechanical properties [1]. Z-pinning is a TTR technique best suited for prepreg material systems. Z-pins while not very effective in suppressing the initiation of cracks, offer an effective solution to resisting large unstable crack propagation. For example, the resistance to propagation of a mode I dominated crack in Z-pin reinforced composites can be increased by factors in excess of 20 times [1].

Most commonly, Z-pins are made from rods of carbon fibre composite less than 1 mm in diameter and inserted in the thickness (Z) direction of composites. They are generally inserted into the laminate using an ultrasonically assisted insertion technique known as UAZ®, orthogonal to the laminate plane before curing in the autoclave. Current applications of Z-pins to date include formula 1 cars and military aircrafts [1,2].

Z-pins cause an increase in resistance to delamination propagation by exerting bridging tractions on the crack interfaces opposing the opening and sliding displacements. The bridging behaviour of individual Z-pins in composites characterized by Yasaee et al. [3], showed that Z-pins provide high energy absorption at low mode mixities where the pull-out failure mode is dominant. However, at high mode mixity ratios, the Z-pins are no longer capable of pulling-out and therefore fail through splitting and rupture, hence providing much lower energy absorption. The superiority of Z-Pin behaviour in Mode I relative to Mode II is one that is reflected even in fatigue data [2]. Z-pins in Mode II are approximately 3 times less effective at increasing the ΔG_{II} initiation value compared to Mode I cases. Moreover, the ΔG_{II} value before the fatigue crack growth is unstable [2]. In spite of the performance disparities of Z-pins in Mode I and Mode II being raised, there is little research work presented in the open literature that offers solutions to these issues. This is particularly important for the case of out-of-plane impact, where the resulting delamination cracks are driven by mode II shear.

The final location of the Z-pins in cured composites are often offset from the vertical z-axis of the laminate, on average by 12–15° for quasi-isotropic laminates and 8–10° for unidirectional laminates - a range which is amplified when the Z-pin diameter increases [1–3]. Offset Z-pins in composites are caused by the deflection of Z-pins during insertion and Z-pin rotation as the composite consolidates during cure

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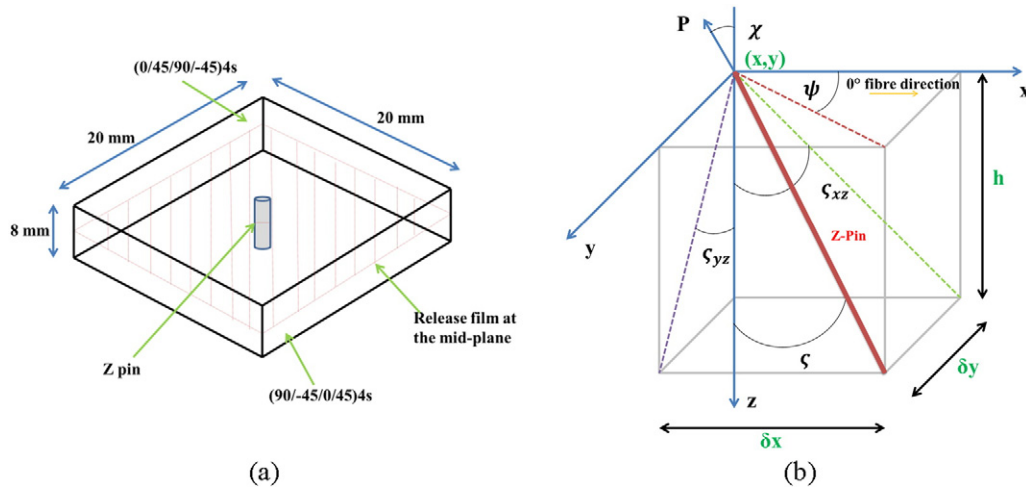URL: http://www.bristol.ac.uk/composites/ (B. M'membe).

Fig. 1. (a) Single Z-pin specimens and (b) specimen axis system.

[4]. Z-pins offset from the vertical are particularly problematic during the manufacture of single pin specimens, thus making it difficult to analyse single pin bridging cases [5]. For high mode mixity load cases, Z-pins offset with the nap with respect to the loading direction show pull-out failure and those loaded against the nap have rupture failure [6]. Overall, offset Z-pins will increase the Mode II energy absorption of composites via increasing the snubbing effect [3,6,7].

The change in the failure mode of offset Z-pins can be exploited to improve bridging capacity in composites where shear loading is predominant. In civil engineering, inclined steel fibres have been shown to increase the energy absorption of reinforced cement [8-9]. For stitched carbon fibre reinforced composites, inclined threads have been shown to increase the maximum force before failure during Mode I loading [10,11]. Furthermore, inclined Z-pins are used to reinforce commercially available sandwich panels such as X-Cor® and K-Cor® [11]. In spite of this, there is little application of the concept to laminated composites outside the scope of a preliminary study carried out by Rugg et al. [12]; in one of the earliest Z-pin related research. Rugg et al. [12] tested 1.7 mm diameter pultruded carbon fibre pins inserted at 39° ± 1 in a truss like array pattern similar to X-Cor® for lap joints and showed a twofold increase in the shear strength of the composite. In addition to this, Cartié et al. [6] in a study to understand crack bridging mechanisms of Z-pins, characterized the behaviour of T300/BMI Z-pins in uni-directional (UD) carbon fibre/epoxy laminates for insertion angles from −10° to 15° under shear loading. However, the test range considered was too limited to show significant variations in energy absorption within the experimental scatter. In the same study, additional tests were conducted on Titanium Z-pins for insertion angles from −30° to 40° however, the failure mechanism of metallic Z-pins differs from that of composite Z-pins and therefore is of less relevance for this current study. No study to date has looked at the resistance of an

inclined Z-pin to Mode II delamination propagation, where the concept is expected to enhance performance relative to orthogonally inserted pins. In this investigation the bridging effect of T300/BMI Z-pins in Mode II has been studied by changing their orientation in a laminated composite. At coupon level, a study analysing the effect of insertion angle on the mechanisms of crack bridging behaviour of single Z-pin specimens is presented. The fundamental findings from this study are then compared on a more structural level by analysing the Mode II resistance of inclined pins using the End-Loaded Split (ELS) specimens.
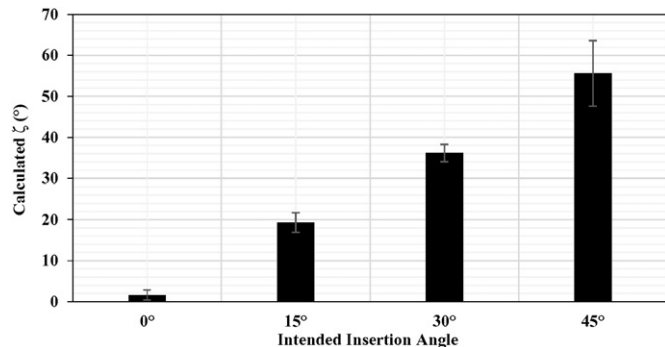

Fig. 3. Mode II single pin specimen test set up.
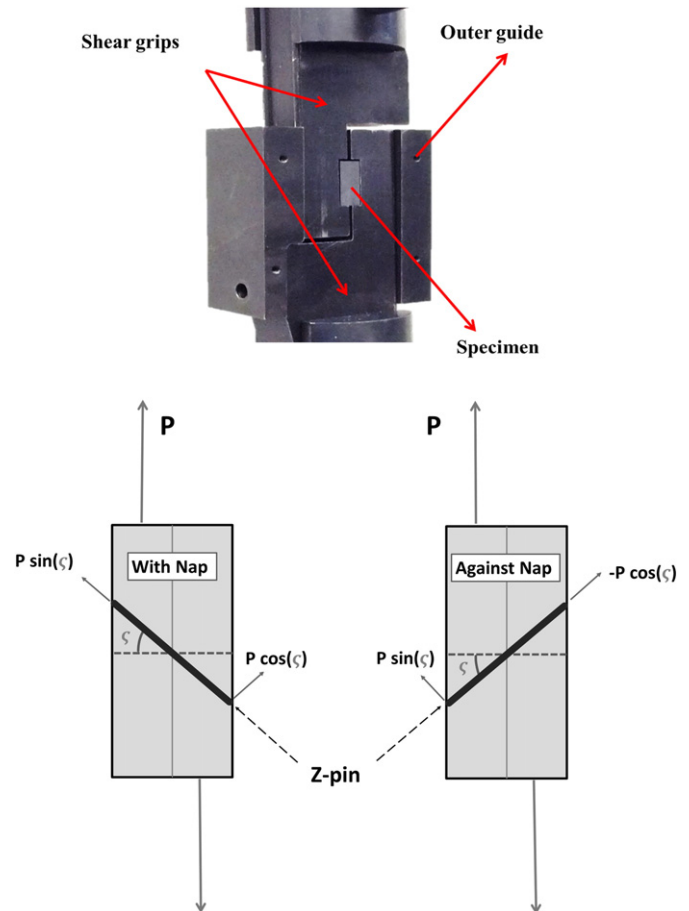

Fig. 2. Effective insertion angles (ς) of the tested specimens.
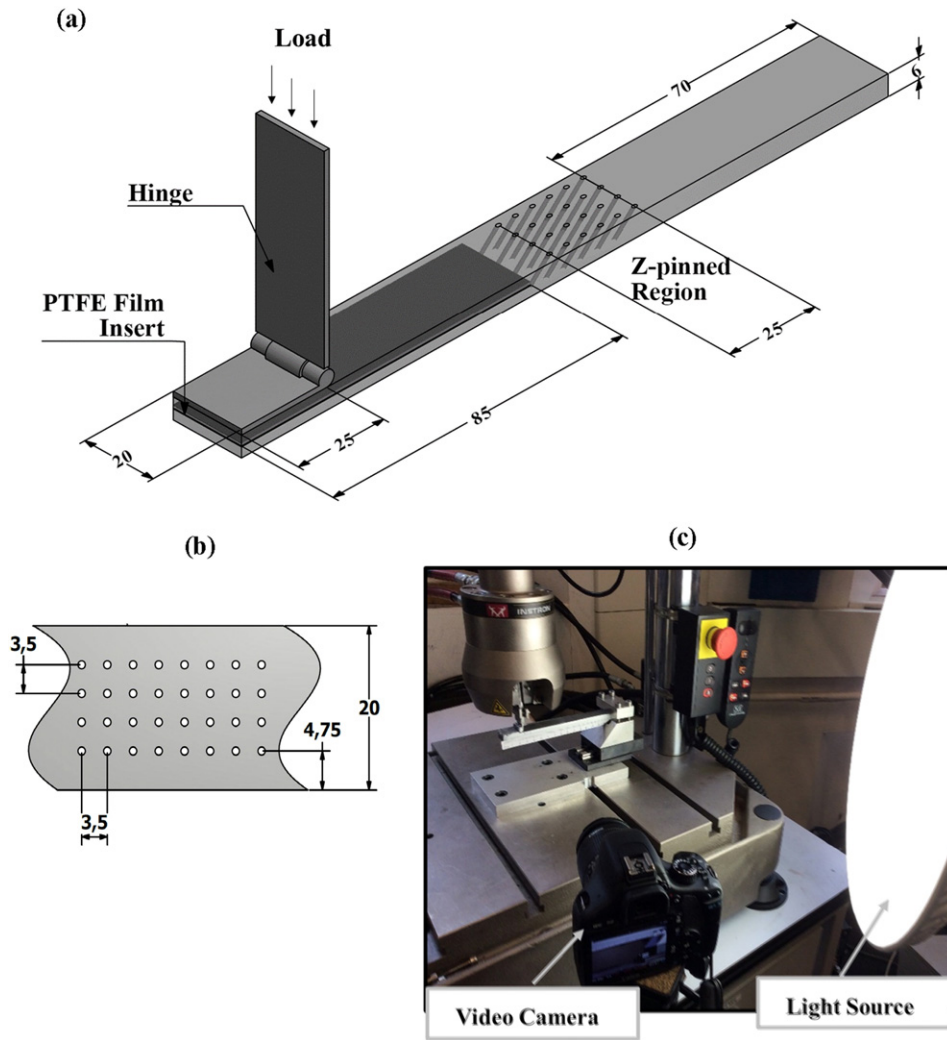
Fig. 4. (a) Schematic diagram of ELS specimens; (b) schematic diagram of Z-pinned region; (c) picture of ELS test-set up.

2. Materials and experimental techniques

Quasi-isotropic (QI) laminates of carbon/epoxy IM7/8552 prepreg tape, supplied by Hexcel, were reinforced with T300/BMI Z-pins of diameter 280 μm. Single pin specimens were machined from a laminate with a $[0,+45,90,-45]_{4s}$ layup in the top half and a $[90,-45,0,+45]_{4s}$ layup in the bottom half, to make $20 \times 20 \times 8$ mm composite block specimens (see Fig. 1). A layer of PTFE film was inserted at the mid-plane during lay-up, to ensure that only the bridging behaviour of the Z-pin was tested. Prior to curing, T300/BMI Z-pins were inserted into the laminate at insertion angles (ς_{xz}) of 0, 15, 30 and 45°. Fig. 1b shows the axis system and the angles used to define the position of the Z-pins in the specimens.

The effective insertion angles of a Z-pin with respect to the z-axis (ς) and the x-axis (ψ) are defined by Eqs. (1) and (2) respectively.

$$\tan\varsigma = \sqrt{\tan \varsigma_{xz}{}^2 + \tan \varsigma_{yz}{}^2} \tag{1}$$

Table 1
Z-pin test specimens.

Specimen configurations		Number of specimens
Unpinned		4
0 degree pin		3
45 degree pin		4
−45 degree pin		2
±45 degree pin		4
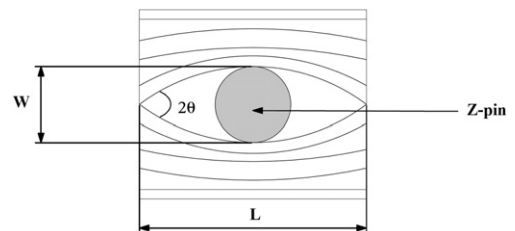
Fig. 5. Schematic representation of the resin rich region around a Z-pin.

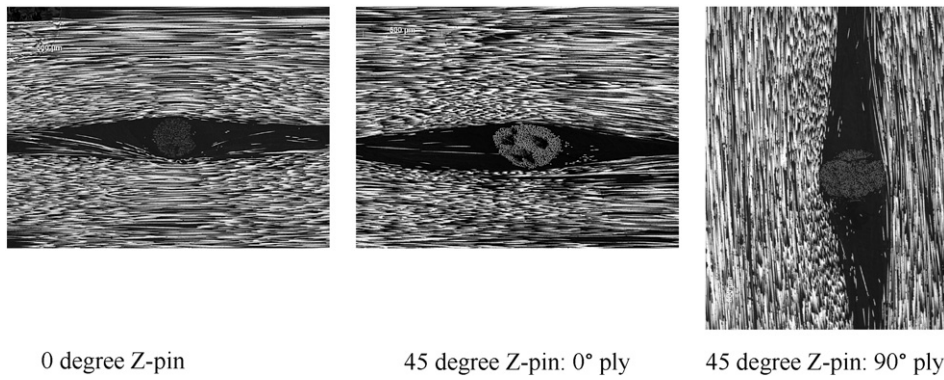0 degree Z-pin · 45 degree Z-pin: 0° ply · 45 degree Z-pin: 90° ply

Fig. 6. Comparison of resin rich region around a 0 degree inserted Z-pin and 45 degree inserted Z-pin in a QI laminate.

$$\tan \psi = \frac{\tan \varsigma_{yz}}{\tan \varsigma_{xz}} \quad (2)$$

During testing, the Z-pins are loaded in Mode II (i.e. $\chi = 90°$). Therefore an inclined Z-pin is subjected to a shear force acting on its cross section and an axial force acting along its longitudinal axis, defined as

$$P_{shear} = P\sqrt{\left(\sin^2\psi + \cos^2\psi \cos^2\varsigma\right)} \quad (3)$$

$$P_{axial} = P(\sin\varsigma \, \cos\psi). \quad (4)$$

The load mode mixity (ϕ) of the Z-pinned specimen, defined as the ratio of the shear forces to the total forces acting on the Z-pin, is given by

$$\phi = \sqrt{\left(\sin^2\psi + \cos^2\psi \cos^2\varsigma\right)}. \quad (5)$$

The mode mixity for the specimens tested ranged from 1.00–0.993. The average effective Z-pin insertion angles (ς) for the specimens are shown in Fig. 2. The main cause for the increase in the effective insertion angle from the intended insertion angle, is sliding of the Z-pins on the surface of the laminate during insertion. Thus higher insertion angles make it easier for the Z-pins to deviate from the intended insertion angle.

The single pin specimens were tested on an Instron 8872 universal testing machine with a 1 kN load cell at a rate of 0.5 mm/min until

failure. The single pin test rig, shown in Fig. 3, consists of two shear grips, which apply a sliding force on the specimen, and an outer guide to constrain out of plane opening. Tests were conducted with the specimens loaded with the nap, and against the nap, with respect to the load vector [6]. Inclined Z-pins loaded with the nap reduce the angle between the long axis of the Z-pin and the local load vectors while those loaded against the nap increase the angle. A full description of the experimental procedure is given by Yasaee et al. [3].

Fig. 4 shows the specimen geometry and test set-up for the ELS test procedure. The specimens were tested in accordance with the European Structural Integrity Society (ESIS-TC4 01-04-02) test procedure [13] at a load rate of 2 mm/min. The tests were carried out on a calibrated 8872 Instron machine with a 10 kN loadcell. Crack propagation was recorded using high resolution camera capable of resolving the crack tip to a ±0.5 mm accuracy. Each specimen was machined from a panel with a layup of $[0,90,+45,-45]_{6s}$ to the geometry shown in Fig. 4. Z-pins were inserted into the uncured laminate, at correct locations for the final machining of the specimens, with a nominal areal density of 0.4%. The first row of z-pins, when measured at the top of the specimen, was at a distance of 10 mm from the initial crack tip. A relatively low areal density in comparison to the conventional standard of 2% is used here in order to overcome the difficulty in controlled manufacturing of inclined Z-pinned composites at such high insertion angles. The following specimen arrangements were considered: unpinned (control), conventional insertion (0°), with the nap (45°), against the nap (−45°), and ±45° (see Table 1). The specimens were clamped 110 mm ahead of the load-line. Prior to testing, a natural crack was propagated by 5 mm beyond the film insert edge
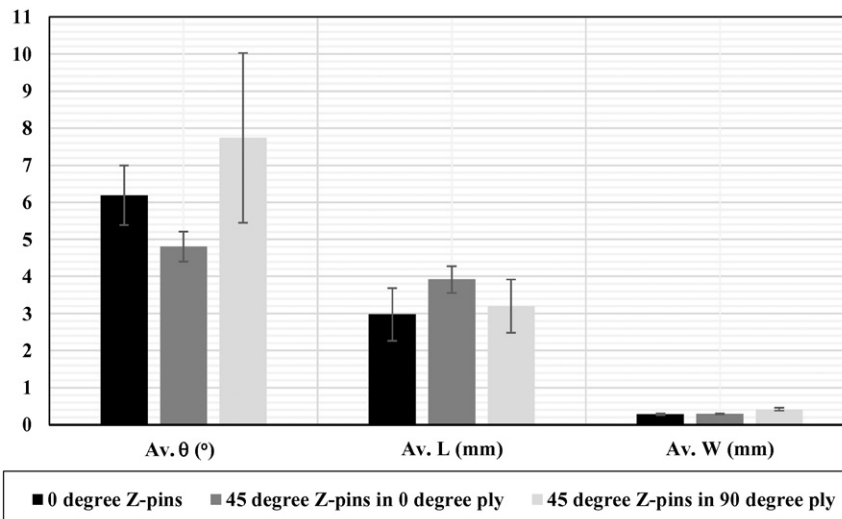

Fig. 7. Effect of insertion angles on resin rich region around the Z-pin.

using a Mode II load. During testing, unstable delamination growth was prevented by ensuring that each specimen was clamped such that the ratio of crack length over the span of the beam prior to testing was greater than 0.55 [13].

3. Results and discussion

3.1. Z-pin microstructure

A resin rich region develops around the Z-pin when the in-plane fibres are pushed apart by the Z-pin during insertion. This tends to create wavy in-plane fibres which have been shown to be detrimental to in-plane properties [1]. The resin pocket is defined by L, its length, W its maximum opening width and θ the resin pocket half angle (Fig. 5). Smaller eyelet angles are desirable because they reduce fibre waviness. For Z-pins inserted orthogonally into the laminate surface, the maximum width of the resin pocket is equal to the diameter of the Z-pin across all layers. However, with inclined Z-pins, the maximum width of the resin pocket increases with Z-pin misalignment, in the direction perpendicular to the fibre direction as shown in Fig. 6.

Fig. 7 shows statistical data on the resin rich features for 0 degree inserted Z-pins and 45 degree inserted Z-pins. The graph shows that θ, and consequently the in-plane fibre waviness in 0° plies is reduced for inclined Z-pins. However, a higher resin pocket half angle is subtended in off-axis plies, a feature which reaches a maximum in 90° plies. On average, θ in 90° plies for 45 degree inserted Z-pins is increased by 2.95° compared to 45 degree Z-pins in 0° plies. Compared to 0 degree inserted Z-pins, 45 degree inserted Z-pins in 90° plies increase the resin pocket half angle θ by 1.6°. Assuming that the 0° plies are the primary load bearing layers, this would in theory indicate that inclined Z-pins will not degrade the in-plane properties significantly more than 0 degree Z-pins because the increase in fibre waviness occurs in off-axis plies, which are not the primary load carry fibres in most structures.

The length of the resin rich region, L, is greatest for the inclined Z-pin in a 0° ply. An increase in length L is synonymous with a reduction in the ply waviness angle, θ. The 0 degree Z-pins have the lowest value for L even compared to the inclined Z-pins in the 90° ply. There are no significant differences in the maximum width of the resin rich region W for inclined and non-inclined Z-pins in 0° plies due to similarities in individual Z-pin diameters. However, in 90° plies, changes in the effective cross section of the Z-pin with respect to the horizontal plane results in an increase of 47% in W compared to the 0° ply value for the inclined Z-pins. It has been previously reported that the maximum opening of the resin rich pocket increases with misalignment in UD laminates [14]. This study confirms those findings and clarifies that increases in W are only observed where the misalignment occurs in a direction away from the in-plane fibre orientation. Increases in W, such as is reported here, are significant since they are associated with the an increased propensity to form merged resin pockets [14].

3.2. Crack bridging behaviour of inclined Z-pins

An important benefit of inclined Z-pins is the ability to manipulate the forces acting on a Z-pin during delamination failure. At low mode mixities, inclined Z-pins are a simple way to increase the embedded length of the Z-pins in composite which would therefore allow for higher frictional energy during pull-out failure. At higher mode mixities as is the case here, inclined Z-pins loaded with the nap reduce the effective Z-pin misalignment angle with respect to the load vector under shear loading, thus encouraging pull-out failure. Figs. 8 and 9 show the maximum load before shear failure of the Z-pins and the energy absorption (i.e. the area under the load–displacement plot) from single Z-pin specimens loaded with and against the nap in Mode II. The maximum load and the energy absorption for specimens loaded with the nap increases with insertion angle. The energy absorption of the Z-pins increases from an average of 8 mJ to 25 mJ when the insertion angle is
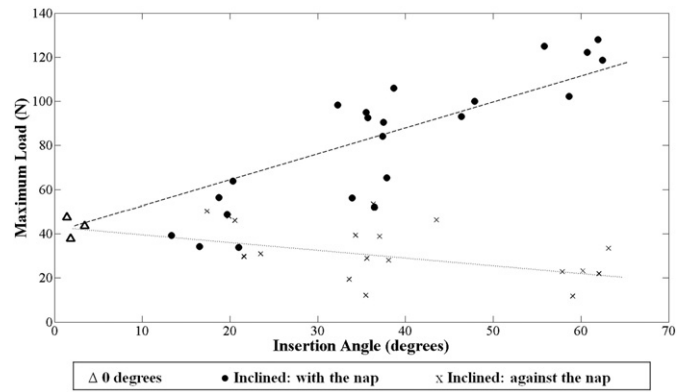

Fig. 8. Maximum load vs. insertion angle under Mode II loading.

increased from 0° to 60°. This increase is due to an increase in axial force P_{axial} acting on the pin as the insertion angle ς increases. As a result, Z-pin specimens with higher insertion angles show evidence of partial pull-out when loaded with the nap.

In contrast, specimens with Z-pins loaded against the nap show a reduction in the both the maximum load and the energy absorption with increasing insertion angle. The changes in behaviour between specimens loaded with nap and against are more prominent at insertion angles greater than 25°. High insertion angles mean that any axial forces on the pin act in compression, which might possibly account for the earlier failure. Fig. 10 shows the partial pull-out in a 45 degree inserted Z-pin compared to the transverse shear rupture failure seen in 0 and −45 degree insertions.

3.3. Mode II delamination resistance of inclined Z-pins

Fig. 11 shows representative ELS load–displacement plots, and the R-curve plots averaged at regular crack lengths, for each type of specimen. Crack propagation in these specimens was either catastrophic or progressive and stable. The delamination resistance of the unpinned specimens was entirely dependent on the matrix properties of the composite. Therefore, crack propagation through the specimens showed a high crack initiation load, followed by a sharp drop in load as the crack propagates through the test region. The presence of the Z-pins in the test region alters the behaviour of the unpinned specimens via the formation of a bridging area in the crack wake that shields the crack front from interlaminar stresses [15]. At sufficient areal densities of Z-pins, this results in an increase in the delamination resistance of the specimens. The length of the crack wake where bridging forces from un-fractured Z-pins are exerted is called the bridging zone length [16]. Thus, increasing the areal density in a Z-pinned region improves delamination resistance by increasing the number of Z-pins at the
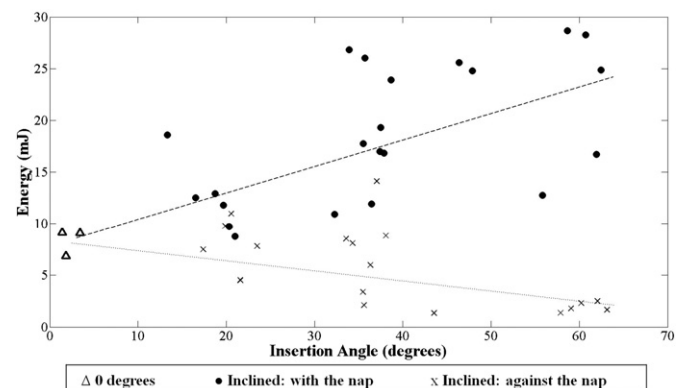

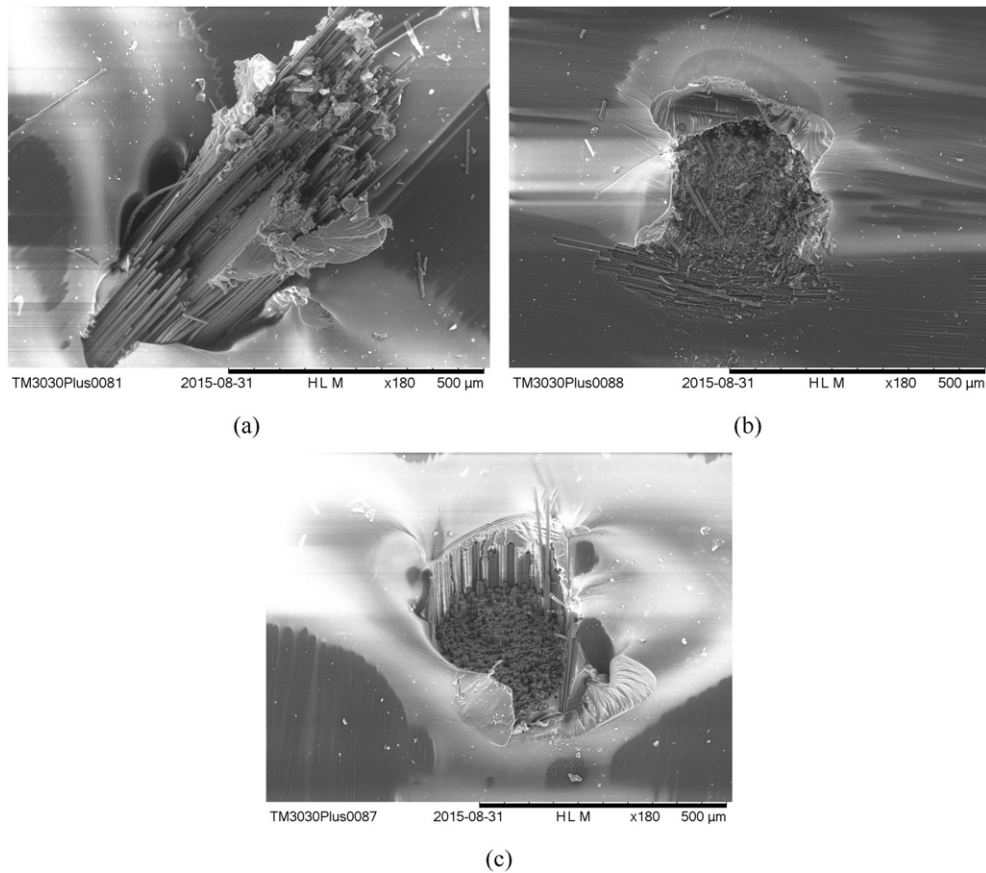**Fig. 9.** Energy absorption vs. insertion angle under Mode II loading.

Fig. 10. SEM images of fracture of Z-pins for (a) 45 degree pin (b) 0 degree pin and (c) −45 degree pin.

crack front and simultaneously shortening the distance between consecutive Z-pins.

Specimens with Z-pins inserted orthogonal to the laminate (0°) are representative of the typical Z-pin configuration using standard manufacturing techniques. These specimens, show a relatively gradual reduction in the maximum load as the delamination propagates through the test region in comparison to the unpinned specimens. A similar behaviour was observed in 3 pt. ENF specimens with 0.5% areal density tested in [17]. However, inconsistencies with stability at low areal densities reported in that study were not observed here. Using the current ELS set-up, the specimens were stable for low areal densities down to 0.22% [18].

Specimens with −45 degree inserted Z-pins are inclined against the nap with respect to the load vector. Therefore, the amount of work needed to rupture the Z-pins in specimens is significantly less than 0 degree inserted Z-pin specimens. Consequently, crack propagation in these specimens, analogous to the unpinned specimens, was highly unstable, resulting in brittle failure of the specimens. Therefore, only one reading for the crack length (a) was taken during testing. In order to account for this on Fig. 11, a dotted line was extended from the initial reading to show the fracture toughness of the −45 degree Z-pin specimens relative to the other configurations. Overall the −45 degree Z-pin specimens produced inconclusive results. For some specimens, (such as the one shown in Fig. 11), specimens loaded against the nap had a load drop larger than that of unpinned specimens; thus showing increased instability. It should be noted however, that the areal densities investigated in this study are not representative of the typical ranges of areal densities for most applications. For such areal densities, usually 1 to 2%, it is likely that the specimen stiffness will increase significantly beyond that of the unpinned specimens.

Specimens with 45 degree Z-pins highlight the potential benefit of aligning the Z-pins with the load vector. Loading with the nap means

that there is an increase in axial force acting on the Z-pin in the bridging length. The result is stable crack propagation and a 22% increase in the maximum load of the specimens relative to the 0 degree pins. The lag in attainment of the maximum load, as shown in Fig. 11, is caused by the partial pull-out of the Z-pins and the development of a bridging zone. As a result, the resistance to crack propagation increases with increasing crack length, up to a limit. This limit cannot be deduced in these tests due to the limitations in the size of the test specimens.

3.4. ±θ Z-pinned laminate

The fundamental principle behind inclined Z-pins is the capacity to increase delamination resistance by reducing the angle between the longitudinal axis of the Z-pins and the loading vector. In this way, the fibres in the Z-pins will be able to simultaneously carry the shear loads as well as promoting pull-out — a highly effective energy absorbing process. However, inclined Z-pins misaligned with the load vector as is the case with the −45 degree specimens, have adverse effects on the apparent fracture toughness of the composite. Thus, the main obstacle to the use of inclined Z-pins aligned only with the load vector would be the challenge in understanding localised load vectors in composite structures. In order to account for this, in a more general case of shear loading, additional samples were manufactured with the Z-pins inserted in a ±45 degree configuration as shown in Table 1.

Figs. 12 and 13 show how the ±45 degree specimens compare to the conventional 0 degree Z-pins specimens. On average, the ±45 degree specimens have a 10% increase in the maximum load in the Z-pinned area and therefore the apparent fracture toughness of the specimens is increased. The load–displacement plot of the ±45 degree specimens show a combination of the failure mechanisms of the 45 degree and −45 degree specimens. Similar to the 45 degree specimens, crack propagation is stable and the maximum load is

Fig. 13. Averaged G_{IIC} plots comparing the configurations of the 0 degree and ± 45 degree specimens.
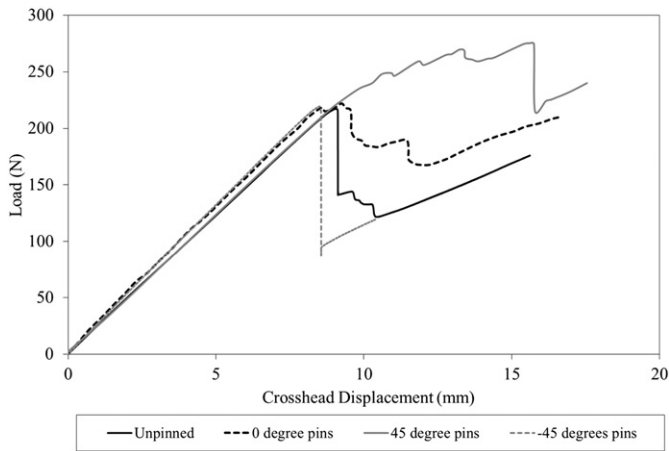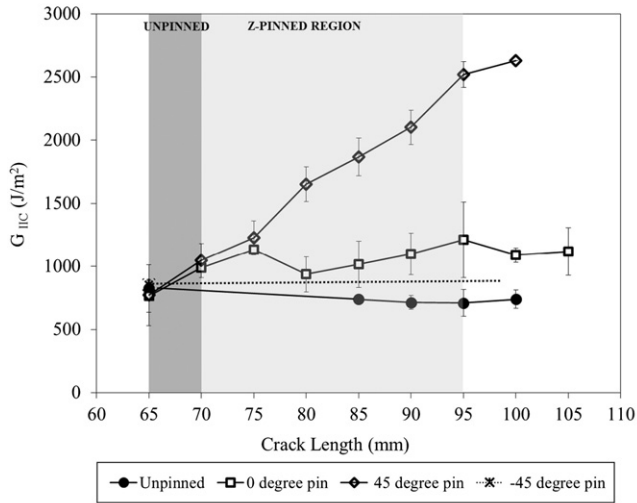
Fig. 11. Graphs of Mode II ELS results for specimens containing 0.4% density Z-pins with various insertion angles showing: (a) load vs. crosshead displacement plot and (b) R-curve plots.

increased due to partial pull-out from the 45 degree pins. However, the extension of the bridging zone of the pins, which was observed in the 45 degree pins is reduced due to the presence of the -45 degree pins. Therefore, it is possible that at the higher areal densities normally used for commercial applications, greater differences in the apparent fracture toughness between the two configurations may occur. The
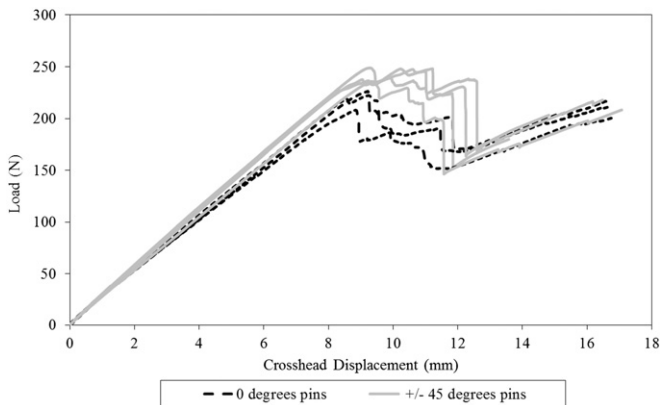

Fig. 12. Load–displacement plots comparing the high density configurations of the 0 degree and ± 45 degree specimens.
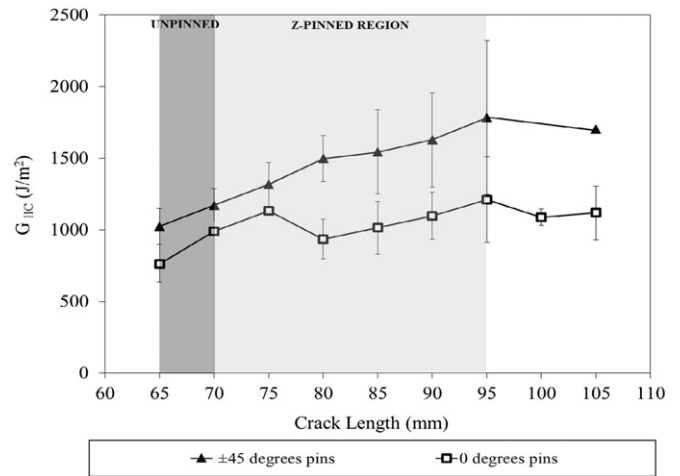
effects of high stiffness from the -45 degree Z-pins coupled with high apparent G_{IIC} propagation values (due to partial pull-out) from the 45 degree Z-pins may become more prominent at high areal densities. Further studies are needed to verify this. These results are particularly useful for the design of Z-pinned composite joints where the load vector can be predicted relatively easily, such as lap-joints.

4. Conclusions

Aligning a Z-pin with the load vector ensures that the dominate forces acting on the Z-pin are frictional forces as opposed to shear forces which cause Z-pins to fail catastrophically resulting in low energy absorption. This is best demonstrated by traditionally inserted Z-pins (0 degree insertion angle) loaded in mode I. In this case, the Z-pin insertion angle is directly aligned with the load vector. As a result, delamination propagation is resisted by frictional forces of the Z-pin during pull-out failure, which is a high energy failure mode. However, at high mode mixities such as mode II, direct alignment of Z-pin longitudinal axis with the load vector is not possible. In these cases, this papers recommends insertion angles which reduce the angle between the long axis of the Z-pin and the local load vectors. For the angles selected in this study, that is 0, 15, 30 and 45 degrees, it has been shown that there is a consistent trend of increasing Mode II delamination resistance for Z-pins (loaded with the nap) with increasing angle of insertion. Energy absorption of a single pin specimen showed a twofold increase in the Mode II maximum load when the angle of insertion was increased from 0° to 60°.

For Mode II delamination tests, increasing the insertion angle to 45 results in a 22% increase in maximum load compared to conventional Z-pins inserted at 0 degrees. This behaviour is attributed to a rise in axial force acting on the pin as the insertion angle increases. However, Z-pins loaded against the nap have combined shear and compressive loading which results in brittle Z-pin fracture and subsequent catastrophic failure of the specimens. Therefore, it is important to ensure a controlled insertion as well as loading of Z-pins in structures, to make certain that loading against the nap is avoided. In addition, it is important to ensure a good understanding of loading vectors on a component so that an optimal Z-pin insertion angle is selected. In order to create a configuration more suitable for general shear loading cases, specimens with ± 45 degree Z-pins have been proposed. Even at the low areal densities tested here, the ± 45 degree configuration is better at resisting mode II delamination propagation compared to the 0 degree configuration. It is expected that at higher areal densities (1–2%), which are normally used for Z-pinned composites, the anticipated rise in fracture

toughness for all the cases will be highlighted more clearly. Finally, the use of inclined pins may also provide the added benefit of reducing the ply waviness in the load bearing plies.

Acknowledgements

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