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DELAMINATION RESISTANCE OF COMPOSITES USING INCLINED Z-PINS

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ABSTRACT

This study explores the behaviour of inclined Z-pins inserted in End Loaded Split (ELS) specimens at areal densities of 0.22% and 0.40%. The study has shown an increase in the fracture toughness when Z-pins are better aligned with the load vector (inclined) compared to the conventional, orthogonally inserted Z-pins. Brittle, catastrophic failure occurs when the inclined Z-pins are misaligned with the load vector. Given the difficulty in predicting localised load vectors in complex structures, specimens with ±θ configuration are tested and compared to conventional non-inclined Z-pin configurations. The results for the areal densities tested in this study show minimal differences in delamination resistance between the two configurations. However, there is some evidence to suggest that at high areal densities, the ±θ configuration is likely to produce higher G_{IIC} values compared to the conventional non-inclined Z-pin configuration.

1. INTRODUCTION

Laminated composite materials lack through-thickness reinforcement (TTR), which often leads to their failure through delamination. Several TTR techniques such as tufting, stitching, Z-anchoring and Z-pinning have been used to improve the interlaminar strength of the composite by suppressing delamination. Amongst these techniques, Z-pinning is a proven and widely adopted technique, best suited for reinforcing prepreg laminates cured in the autoclave. Application of this technique incurs a modest drop in the in-plane mechanical properties [1].

Z-pins are rods of carbon fibre composite normally less than 1 mm in diameter inserted in the thickness (Z) direction of composites. They are commonly 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 the Northrop F18 and Boeing Sikorsky RAH-66 Comanche military aircrafts [2]. The bridging behaviour of Z-pins in a composite was characterized by Yasaee et. al. [3] where it was shown that Z-pins inserted in a composite provide high energy absorption at low mode mixities where a pull-out failure mode is dominant. However, at high mode mixity ratios, rupture failure is dominant and hence lower energy absorption occurs. Therefore, logic dictates that by aligning the Z-pin with the load vector presiding over a composite component, the energy absorption of Z-pinned composites may be increased. M'membe et al. [4] showed that it is possible to double the energy absorption of a single Z-pin composite sample under Mode II loading by increasing the angle of insertion from 0° to 45°. While this concept is readily transferable, for the majority of structures the direction of the local load vector is not always predictable. In the current study, we demonstrate a general approach to how inclined Z-pins can be used to improve the mode II delamination resistance compared to orthogonally inserted Z-pins.

2. MATERIALS AND EXPERIMENTAL TECHNIQUES

Quasi-isotropic laminates of IM7/8552 prepreg tape, supplied by Hexcel, were reinforced with T300/BMI Z-pins of diameter 280μm. The laminate layup was $[0,90,+45,-45]_{6s}$. Figure 1 shows the specimen geometry and test set-up. The specimens were tested using the End-Loaded Split (ELS) test procedure in accordance with the European Structural Integrity Society (ESIS-TC4 01-04-02) at a rate of 2 mm/min [5]. The tests were carried out on a calibrated Instron machine with a 10kN loadcell. Crack propagation was recorded using a DSLR camera.

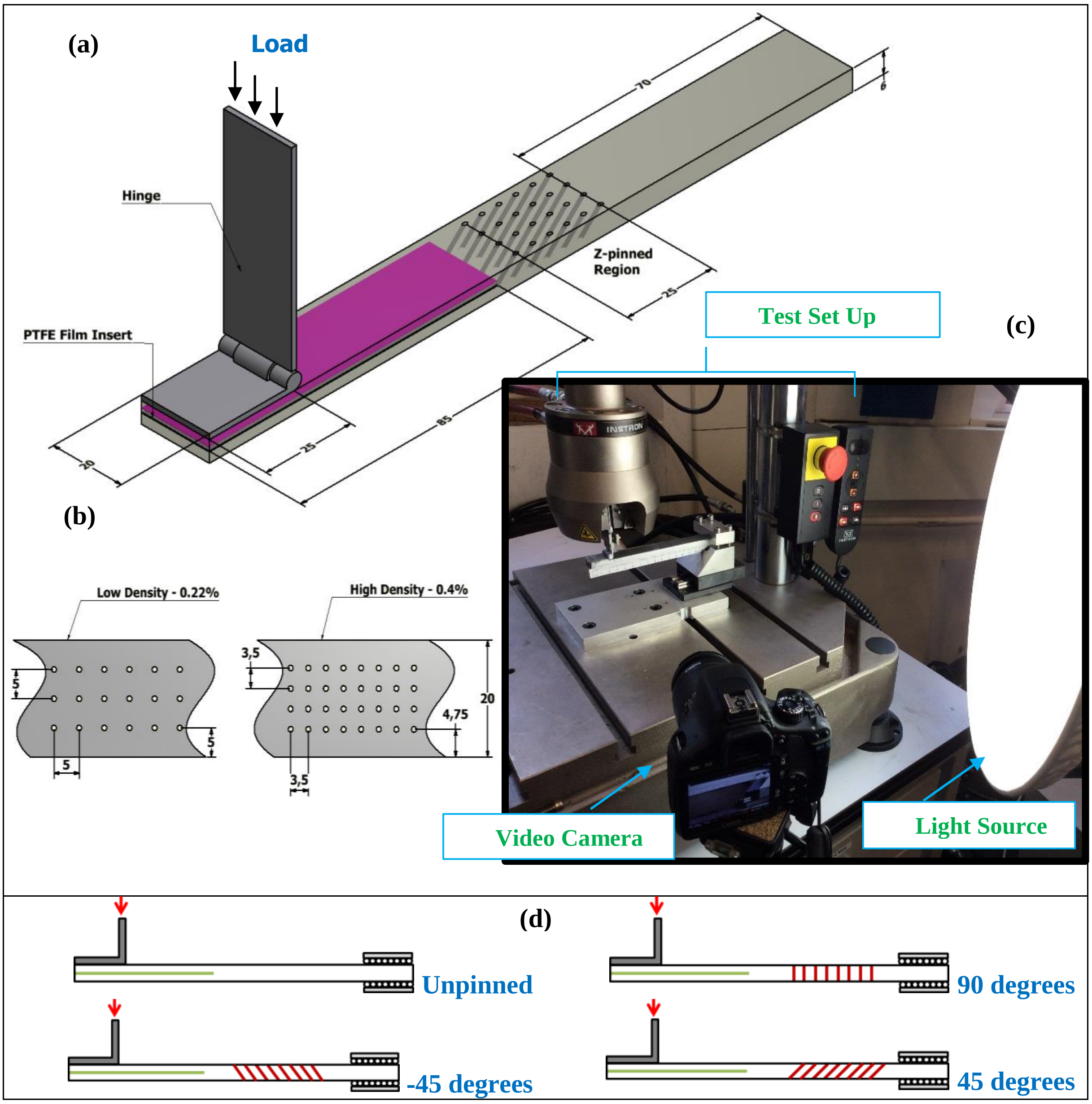


Figure 1. (a) Schematic of ELS specimens; (b) schematic of Z-pinned region at different densities; (c) picture of ELS test-set up; (d) Z-pin test arrangements

Each specimen was machined from a pre-TTR reinforced panel to a size of 190 x 20 mm with a nominal thickness of 6 mm. The edge of the PTFE film insert and the start of the Z-pinned region are located 60 mm and 70 mm ahead of the load-line respectively (figure 1a). The specimen was clamped

110mm ahead of the load-line. Prior to testing, a crack was grown 5mm beyond the film insert edge by clamping the specimen 5mm ahead of the Z-pinned region and loading the specimen until the crack length increased to 65mm. Unstable delamination growth was prevented by ensuring that the specimen was clamped such that the ratio of crack length over the span of the beam prior to testing was greater than 0.55 [5]. In order to ensure accurate Z-pin insertion angles during manufacture, two relatively low areal densities of Z-pins; 0.22% (low density) and 0.4% (high density), were selected. The following specimen arrangements were considered: unpinned (control), conventional insertion (90 degrees), with the nap (45 degrees), against the nap (-45 degrees), and ±45 degrees (see Figure 1d). In each case 4 specimens were tested.

3. RESULTS AND DISCUSSION

Following the analysis of tests conducted, from those with identical Z-pinned configurations, one test was chosen as a suitable representation and included in the figures to follow.

3.1 Effect of orientation

Figure 2 shows representative load-displacement plots of the low-density Z-pinned specimens. Similar to previous Mode II results for Z-pinned specimens, crack propagation was either catastrophic or progressive and stable [6]. For the unpinned specimens, delamination resistance is solely dependent on the matrix properties of the composite. Hence crack propagation through the specimens showed a high crack initiation load, followed by sharp drop in load as the crack propagates through the test region. On the other hand, the delamination resistance of Z-pin reinforced composites is a combination of the composite matrix properties along with the bridging effects from the presence of Z-pins. The Z-pins in the specimens form a bridging area in the crack wake that shields the crack front from interlaminar stresses [7]. The length of the crack wake where bridging forces from un-fractured Z-pins are enforced is called the bridging zone length [8].

Specimens with Z-pins inserted orthogonally (90 degrees) are representative of the conventional, idealised arrangement produced by the Z-pinning process using the UAZ technique (albeit at a lower pin density). These specimens, show a gradual reduction in peak load as the specimen propagates through the test region in comparison to the unpinned specimens. In the literature, similar behaviour was observed in 3pt ENF specimens with 0.5% areal density [6].

Specimens with -45 degree Z-pins are inclined against the nap with respect to the load vector. In this case the shear force component exerted on the Z-pins is increased beyond that of the 90 degree specimens. At the 0.22% areal density shown in figure 2, these specimens show a high initiation peak load followed by a load drop. The load drop is a result of rapid crack propagation to the periphery of the Z-pinned region. Beyond this point, the crack propagates in a manner analogous to the unpinned specimen. This unstable crack propagation behaviour results in brittle failure of the Z-pinned specimens. Figure 3c shows the pin local fracture surface indicating brittle failure produced by loading against the nap.

In the case of 45 degree Z-pinned specimens, loading with the nap in respect to the load vector means that there is an increase in axial force acting on the pin compared to the 90 degree specimens. The result is stable crack propagation concluded by a small load drop after the Z-pinned region. The delay in reaching the peak load, as seen in figure 2, can be attributed to partial pull-out of the Z-pins and the development of a bridging zone. Figure 3 shows the pull-out in the 45 degree specimens compared to the transverse shear rupture failure seen in -45 and 90 degree specimens.

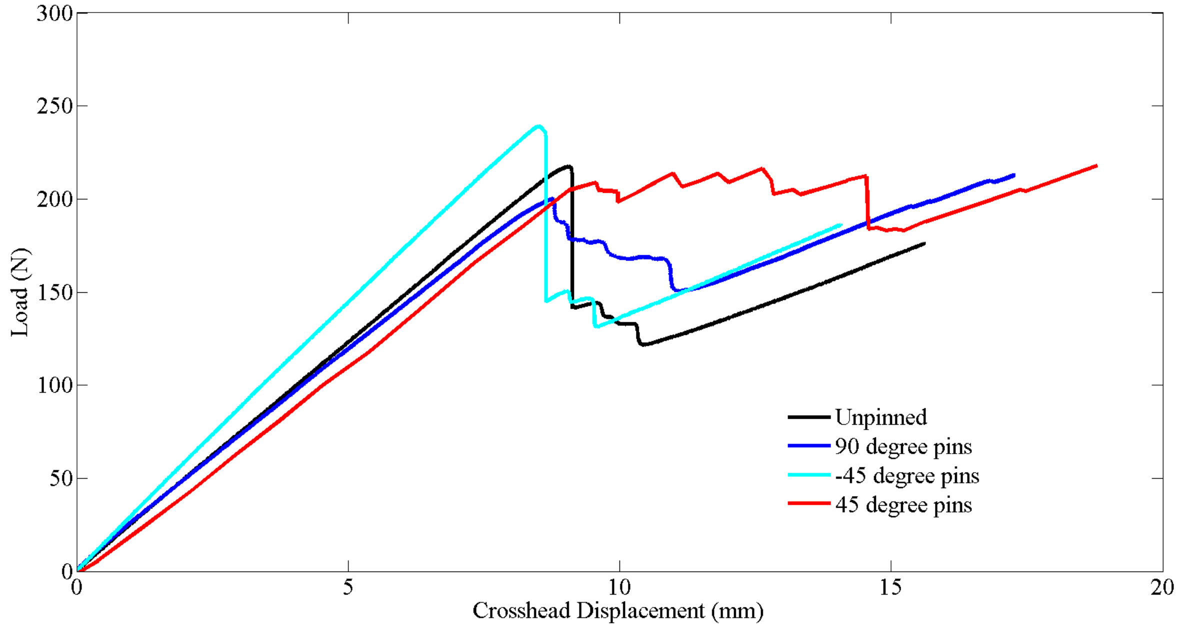
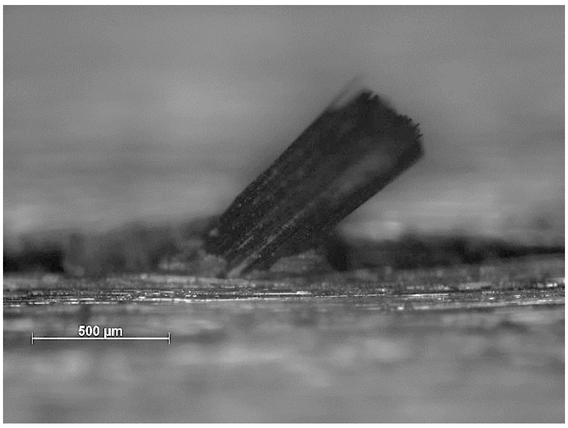
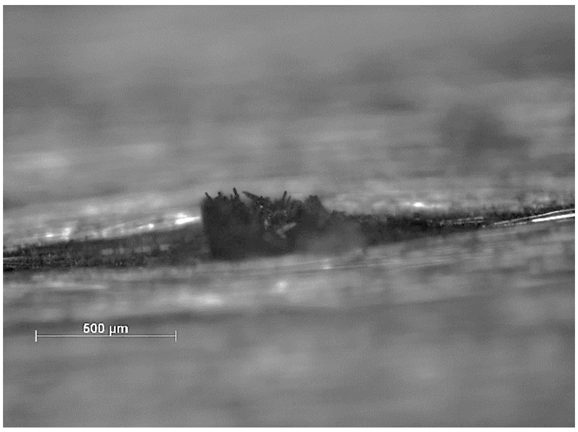


Figure 2: ELS test load vs. crosshead displacement plot for specimens containing 0.22% density Z-pins with various insertion angles.



(a)



(b)

(c)

Figure 3: Fracture of Z-pins for (a) 45 degree Z-pins; (b) 90 degree Z-pins and (c) -45 degree Z-pins

3.2 Effect of areal density

For a given specimen geometry, increasing the areal density increases the number of Z-pins at the crack front and simultaneously reduces the distance between the rows of Z-pins. Therefore, for a given crack length, there is an increase in the number of Z-pins in the bridging length. In addition, the G_{IIC} propagation value of the Z-pinned region is increased. Figure 4 shows the effect of increasing the areal density from 0.22% to 0.4%. Increasing the areal density to 0.4% for the 90 degree Z-pins increased the apparent fracture toughness of the specimens. The peak load was increased by 12% on average as is the load recorded throughout the test region.

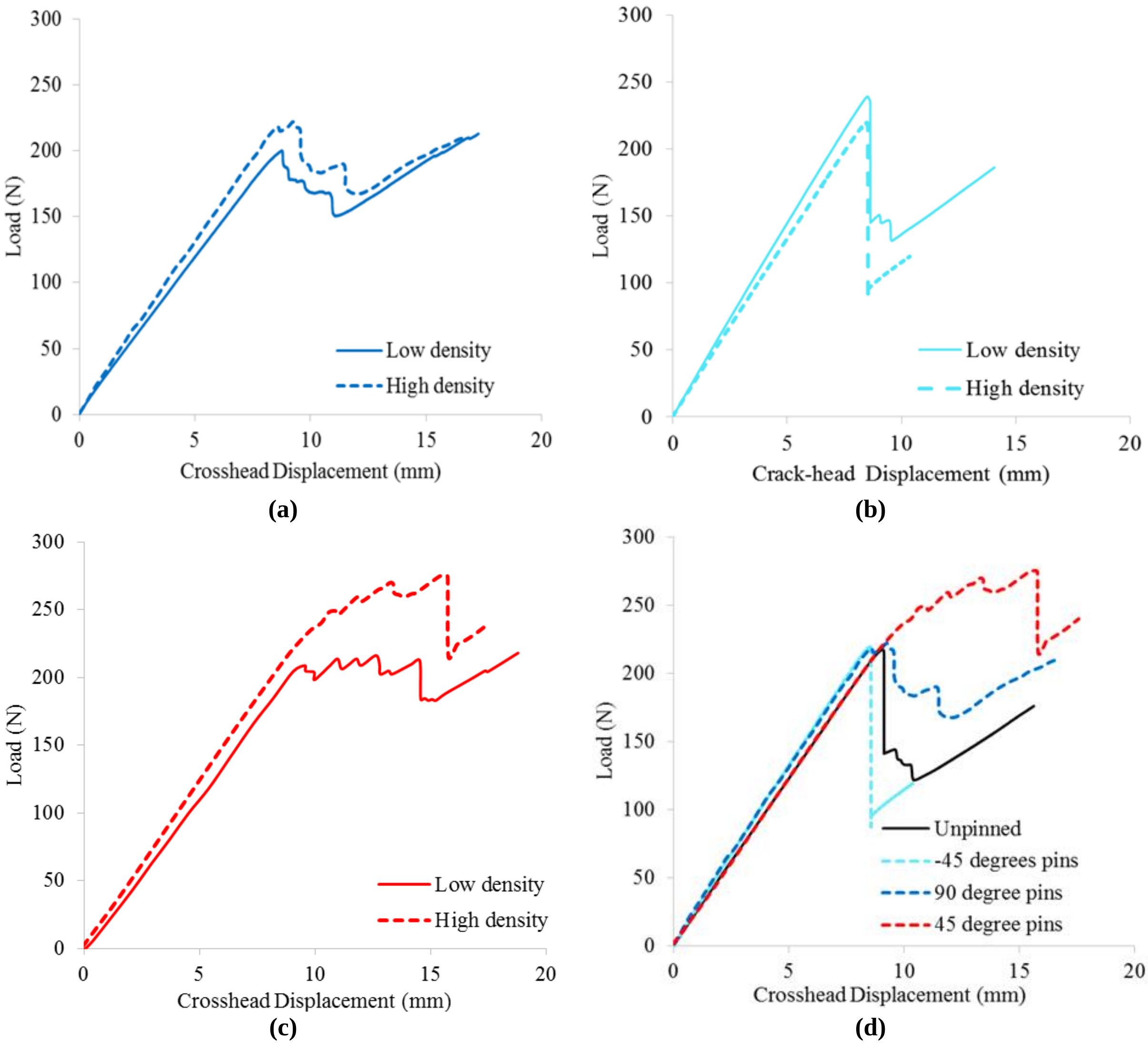


Figure 4: Effect of increasing the density from 0.22% (low density) to 0.4% (high density) for: (a) 90 degree; (b) -45 degree; (c) 45 degree; and (d) comparison high density specimens

Figure 4(b) shows that increasing the areal density of the -45 degree specimens to 0.4% results in a larger load drop; hence showing increased instability. The larger load drop incurred in the higher density specimens is caused by unstable crack growth which propagates beyond the Z-pinned region. The areal densities investigated in this study are not representative of the nominal ranges of areal densities for most applications. For those ranges of areal densities, usually 1 to 2%, it is likely that instability may become more pronounced. Additionally, the specimen stiffness will increase. These results emphasise the importance of a controlled insertion method for Z-pinned composites. Currently, using the UAZ®, the Z-pins in the cured composite are often offset from the vertical z-axis of the laminate, on average by 5-15° [1]. Moreover, direction of the offset is difficult to control. Therefore, in a case where these Z-pins are loaded against the nap with the load vector, the laminate is made increasingly less resistant to shear as the insertion angle is increased. For 0.4% areal density, specimens loaded against the nap are even more unstable than the unpinned specimens.

Figure 4(c) shows that doubling the areal density of the 45 degree specimens increases the peak load on average by 25% for the specimens tested. As a result, the resistance to crack propagation, is increased. Figure 4(d) shows the combined benefit of aligning the Z-pins with the load vector and increasing the areal density. Comparing figure 4(d) to figure 2 shows that the gains in average load propagation values achieved by manipulating the Z-pin orientation in the laminate are more pronounced at higher areal densities.

3.3 A case for the ±θ Z-pinned laminate

The main benefit of 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 pins will be able carry the shear loads as well as promoting the pins to pull-out – a highly effective energy absorbing process. However, if the inclined Z-pin is misaligned with the load vector as is the case with the -45 degree specimens, the result can be detrimental. Thus, the main barrier against the idea of only aligning Z-pins in the laminate with the load vector is the difficulty in understanding load vectors in composite structures. To overcome this, additional samples were manufactured with the Z-pins inserted in a ±45 degrees high density configuration. Figure 5 below shows how this result compares to the conventional 90 degree Z-pins. The load – displacement plot of the ±45 degree specimen shows an amalgamation of 45 degree specimen and -45 degree specimen failure behaviour. The specimens show an initiation peak load with small load drops as -45 Z-pins in each row fracture. Compared to 90 degree specimens, the ±45 degrees specimens exhibit similar behaviour within experimental variations.

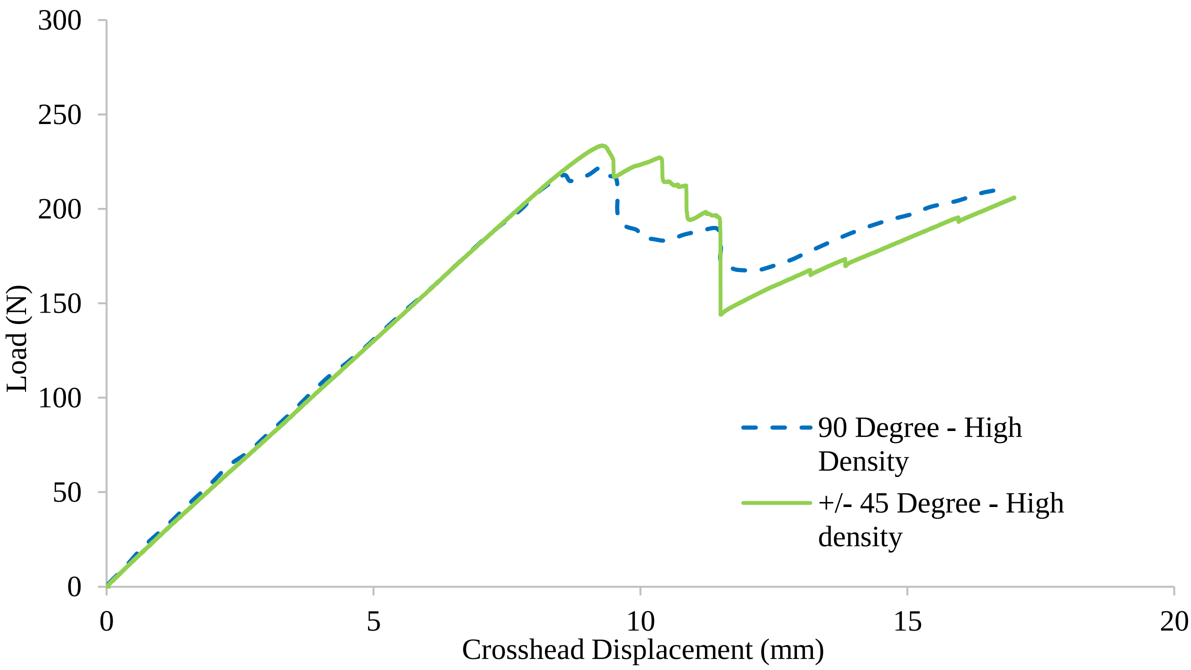


Figure 5: Load-displacement plots comparing the high density configurations of the 90 degree and ±45 degree specimens.

These results are reflected in the fracture toughness values shown in Figure 6. It is important to note that for the specimen geometry and Z-pin array patterns tested here, no plateau value or steady-state crack propagation has been reached. Therefore, it is possible that for areal densities higher than those tested here, vast differences in the apparent fracture toughness between the two configurations may occur. The effects of high stiffness from the -45 degree Z-pins coupled with high G_{IIC} propagation values from the 45 degree Z-pins may become more prominent factors at high areal densities. However, more tests at higher densities are needed to verify this hypothesis.

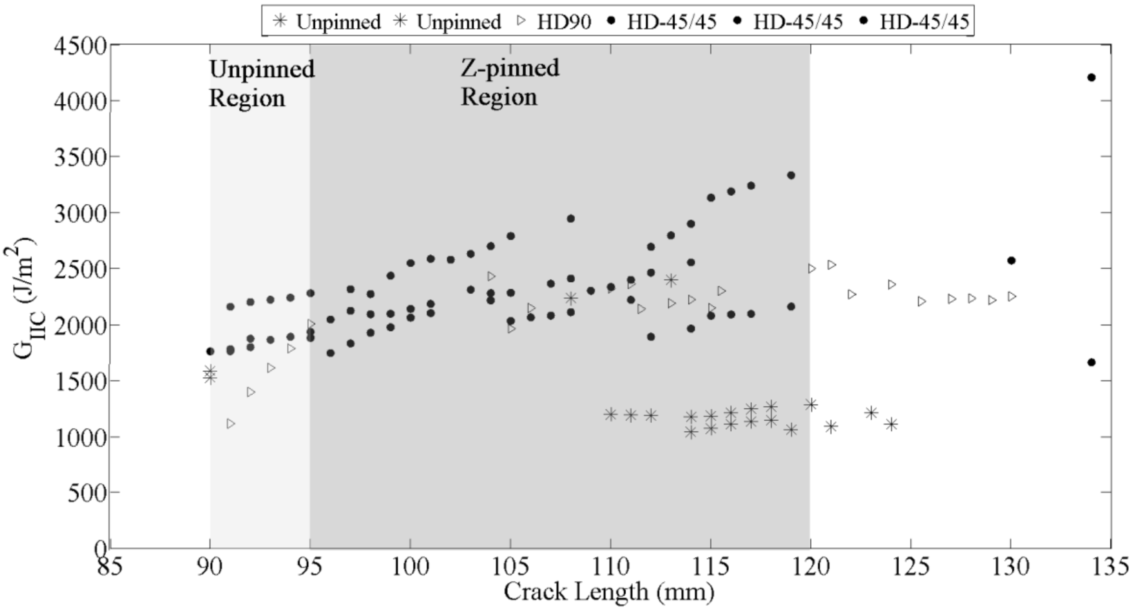


Figure 6: G_{IIC} plots comparing the high density configurations of the 90 degree and ±45 degree specimens.

4. CONCLUSIONS

Inclined Z-pins in previous studies have been shown to improve the Mode II fracture toughness of Z-Pinned composites. This study has shown that for ELS specimens containing 45 degree oriented pins aligned with the nap relative to the load are more stable and increase the fracture toughness of the laminate when compared to conventional Z-pins inserted at 90 degrees. However, when loaded against the nap, increased shear forces on the Z-pins result in brittle Z-pin fracture and subsequent catastrophic failure of the specimens. For the high density specimens tested in this study, loading against the nap induces even greater delamination propagation instability than the unpinned specimens. Therefore, it is important to ensure a controlled insertion technique of Z-pins into structures to make certain that loading against the nap is avoided. Key to this is a good understanding of loading vectors on a component which can inform the pin orientation selection. In order to mitigate the risk, specimens with ±45 degree Z-pins have been proposed. For the areal density tested in this study, the ±45 degree configuration is approximately equivalent to the 90 degree configuration in resisting crack propagation. However, the anticipated gains in fracture toughness for the 45 degree and -45 degree Z-pins at higher areal densities as normally used for commercial applications, are expected to outperform the 90 degree configuration. Additional tests are needed to prove this.

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