EFFECT OF INCLINED INSERTION ON THE DELAMINATION RESISTANCE OF Z-PINNED COMPOSITES

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Abstract

The bridging behaviour of single, inclined Z-pin specimens is studied under Mode I, Mode II and Mixed-Mode loading conditions. The results show that increasing the insertion angle from 0 to 45 degrees has the effect of increasing the delamination resistance by a factor of two under Mode II and Mixed-Mode I/II loading. However, inclined Z-pins have adverse effects on the energy absorbed under Mode I loading.

1. Introduction

Laminated composite materials lack through-thickness reinforcement, which often leads to their failure through delamination. Several through-thickness reinforcement techniques such as tufting, stitching, Z-pinning and Z-anchoring have been used to improving 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. However, application of this technique has to be expected to result in some fibre damage in the prepreg plies, with a consequent drop in the in-plane mechanical properties [1].

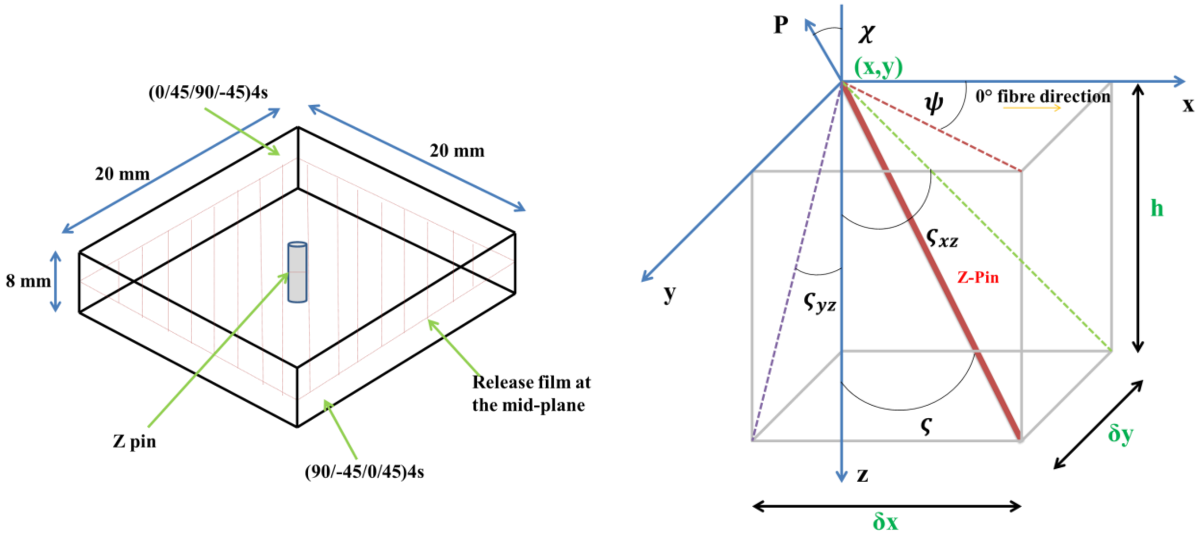
Z-pins are rods of carbon fibre composite normally less than 1 mm in diameter inserted in the thickness direction of composites. They are commonly inserted into the laminate using an ultrasonically assisted insertion technique known as UAZ®, orthogonal to the laminate plane before the curing in the autoclave. The final state of the Z-pins in the cured composite, are often offset from the vertical z-axis of the laminate on average by 5-15°, a range which is amplified when the Z-pin diameter increases [1][2]. The root causes of the offset angles stems from of the deflection of Z-pins during insertion and Z-pin rotation as the composite consolidates during cure [2]. 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 [3]. The effects of offset Z-pins on bridging behaviour was analysed by Cartié et al. [4]. Z-pins offset in the nap with respect to the loading direction showed pull-out failure and those loaded against the nap experienced Z-pin rupture failure. On the whole, offset angles will increase the Mode II energy absorption of composites via increasing the snubbing effect [4][6].

The change in failure Mode of offset Z-pins can be exploited to improve the bridging capacity in composites. In civil engineering, inclined fibres are used to increase the energy absorption of steel fibres reinforced in cement [7]. In stitched composites, inclined threads have been shown to increase the maximum load during Mode I failure [10][11]. Despite the fact that inclined Z-pins are used in commercially available sandwich panels such as X-Cor® and K-Cor®, there is little application of the concept in laminated composites. In the early stages of Z-pin research, Rugg et al. [5] 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. Cartié et al. [4] characterized the behaviour of T300 BMI in UD carbon fibre/epoxy laminate for insertion angles from -10° to 15° under shear loading. However, the test range considered was too limited to produce clear trends. Since then, inclined Z-pins in laminates have not been analysed further. The current study aims to maximise the bridging effect of Z-pins by changing their orientation in the laminate tested subsequently under Mode I, Mode II and Mixed-Mode I/II loading conditions.

2. Materials and Experimental Techniques

2.1. Specimen Manufacture

Quasi-isotropic laminates of IM7/8552 prepreg tape supplied by Hexcel were reinforced with T300/BMI Z-pins of diameter 280 μm as shown in Figure 1a. Each specimen is a 20 x 20 mm block with a nominal thickness of 8 mm. A layer of PTFE film is inserted at the mid-plane during lay-up to represent the presence of a crack.



(a) (b)

Figure 1 (a) Single Z-pin specimens (b) Specimen axis system

Figure 1b shows the axis system and the angles used to define the position of the Z-pins in the specimens. The Z-pin insertion angles in the x-z plane ς_{xz} and the y-z plane ς_{yz} are given by

$$\tan \varsigma_{xz} = \frac{\delta x}{h} \tag{1}$$

$$\tan \varsigma_{yz} = \frac{\delta y}{h} \tag{2}$$

where δx and δy are the changes in the Z-pin position (x,y) between the bottom and top surfaces of the specimen measured under a microscope. During manufacture, T300/BMI Z-pins were inserted into the laminate at insertion angles (ς_{yz}) of 0°, 15°, 30° and 45°.

2.2. Test Set Up

The specimens were tested under Mode I, Mode II and 50% Mixed-Mode loading conditions. The load was applied using an Instron 8872 universal machine with a 1kN load cell at a rate of 0.5 mm/min until failure. Figure 2 shows the test fixture used to conduct the tests. The Mixed-Mode rig used to carry out the Mode I and Mixed-Mode tests, is a two part fixture consisting of two lugs which attach the fixture to the machine and a rotatable disk. The specimen is held in place in the rotatable disk by a pair of screws on the side of the top and bottom halves of the disk. The rotatable disk is connected to the lugs using a minimum of 4 cap screws. The Mode II rig consists of two shear grips which apply force on the specimen and an outer guide to constrain out of plane opening. All Mode mixity tests were conducted with the specimens loaded in the nap with respect to the force vector [4]. A full description of the experimental protocol is given by Yasaee et al. [10].

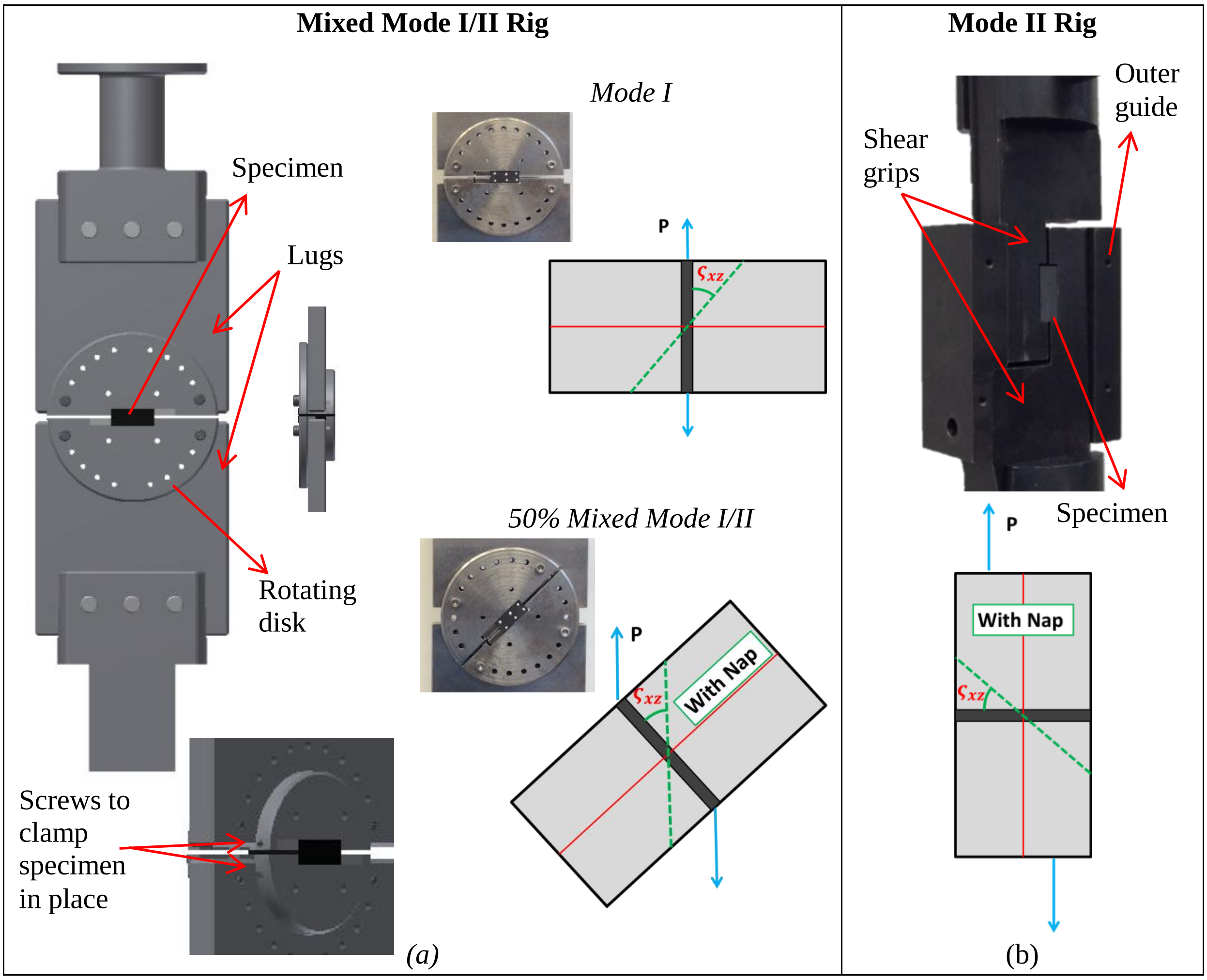


Figure 2 (a) Mode I and 50% Mixed-Mode I/II test set up; (b) Mode II test set up

2.3. Effective insertion angle and Mode mixity

The effective insertion angles of a Z-pin with respect to the z axis (ς) and the x axis (ψ) are defined by equations (3) and (4) respectively.

$$\tan\varsigma = \sqrt{\tan\varsigma_{xz}{}^2 + \tan\varsigma_{yz}{}^2} \tag{3}$$

$$\tan\psi = \frac{\tan\varsigma_{xz}}{\tan\varsigma_{yz}} \tag{4}$$

During testing, the Z-pins are subject to a load P which is rotated through an angle (χ) at intervals of 45° in the x-z plane from 0° to 90°. Therefore, the Z-pins are subjected to a shear force

$$P_{shear} = P\sqrt{cos^2\chi sin^2\varsigma + sin^2\chi(sin^2\psi + cos^2\psi cos^2\varsigma) - \frac{1}{2}\sin 2\chi \sin 2\varsigma \cos\psi} \tag{5}$$

acting on the cross section of the Z-pin and an axial force

$$P_{axial} = P(\sin\varsigma \sin\chi \cos\psi + \cos\varsigma \cos\chi) \tag{6}$$

acting along the Z-pin in the form of a frictional force. The Mode mixities (ϕ) of the specimens is defined as the ratio of the shear forces to the total forces acting on the Z-pins and is given by

$$\phi = \sqrt{cos^2\chi sin^2\varsigma + sin^2\chi(sin^2\psi + cos^2\psi cos^2\varsigma) - \frac{1}{2}\sin 2\chi \sin 2\varsigma \cos\psi} \tag{7}$$

The average effective Z-pin angle and Mode mixity of the specimens are shown in Table 1. Z-pin deflection during insertion is one of the causes for the increase in the effective insertion angle from the intended insertion angle.

Specimen Insertion Angles [°]	***Mode I***		***Mode II***		***50% Mixed-Mode***	
	Effective Insertion Angle [°]	**Mode Mixities**	**Effective Insertion Angle [°]**	**Mode Mixities**	**Effective Insertion Angle [°]**	**Mode Mixities**
0	4.94 ± 1.4	0.09 ± 0.02	1.62 ± 1.2	0.999 ± 0.00	2.48 ± 1.6	0.68 ± 0.01
15	17.6 ± 3.4	0.30 ± 0.06	18.9 ± 3.4	0.961 ± 0.02	18.8 ± 2.1	0.40 ± 0.00
30	35.8 ± 1.1	0.59 ± 0.02	35.8 ± 2.1	0.829 ± 0.04	35.2 ± 2.6	0.16 ± 0.02
45	49.8 ± 3.0	0.76 ± 0.03	51.5 ± 3.6	0.660 ± 0.07	50.6 ± 2.5	0.09 ± 0.04

Table 1 Average insertion angles and Mode mixities. Five specimens are used per test angle for each given loading condition.

3. Results and Discussion

3.1. Inclined Z-pins at low load angles

The maximum load and energy absorption, as a function of the effective insertion angle for Mode I tests is shown in Figure 3 and Figure 4. There is a slight increase in the maximum load as the insertion angle increases. A similar trend was observed in [10] for Z-pins loaded at equivalent Mode mixities. The Z-pins inserted at 0° and 15° pulled out while those of 30° to 45° ruptured. Yasaee et al. [10] studied the failure mechanism of T300/BMI Z-pins under Mixed-Mode loading conditions and showed that there is a transition from pull-out to rupture failure which occurs within a range of 0.544-0.615 Mode mixities. The slight increase in maximum load can be attributed to enhanced friction on the Z-pin due to snubbing effects as the angle is increased [6][7][10]. However, beyond a certain point, the increase in bending stress on the Z-pin leads to fibre failure [9]. Previous studies have shown that the energy required for pull-out failure of Z-pins exceeds that of fibre rupture [1][10]. Consequently the energy absorbed decreases as the insertion angle increases and failure type changes (figure 4). The onset of the transition region is expected to be delayed by using larger diameter pins [11]. Nylon and polypropylene fibres with 508 μm diameter, have been shown to fail via pull-out for insertion angles up to 45° in a cement matrix system [7]. On this account, it would be beneficial to extend this study to larger diameter Z-pins.

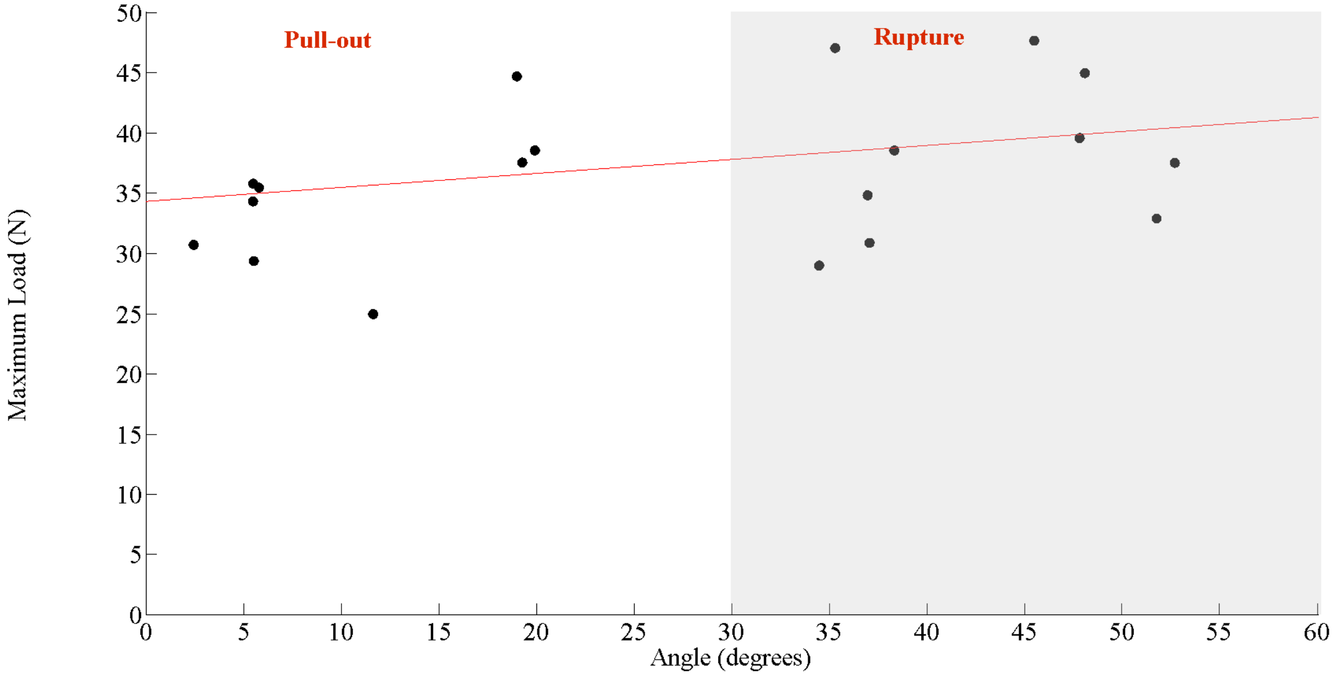


Figure 3 Maximum load vs. insertion angle under Mode I loading

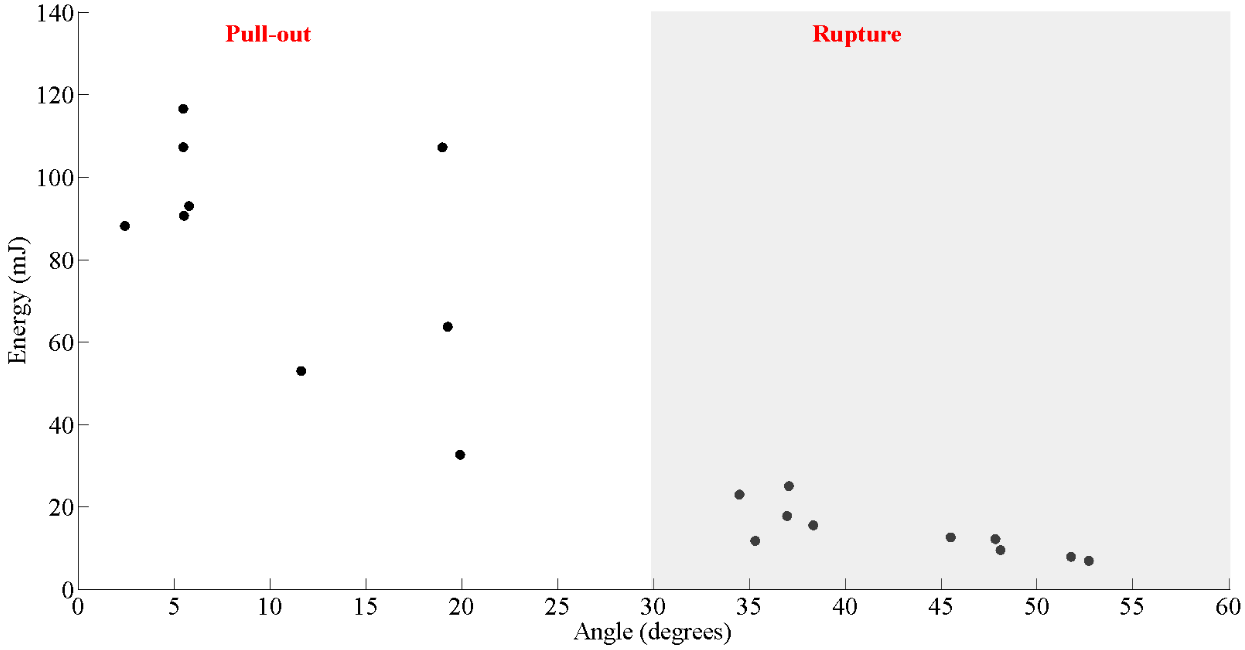


Figure 4 Energy absorption vs. insertion angle under Mode I loading

3.2. Inclined Z-pins at high load angles

An important benefit of inclined Z-pins is the ability to reduce the effective Z-pin misalignment angle with the load vector thus encouraging pull-out failure. Figure 5 and Figure 6 show the maximum load and the energy absorption of Z-pins loaded with the nap under Mode II and 50% Mixed-Mode I/II loading conditions. In both cases, the maximum load and the energy absorption are increasing with insertion angle. The energy absorption of Z-pins increases from an average of 12 mJ to 30 mJ when the insertion angle is increased from 0° to 45° in Mode II.

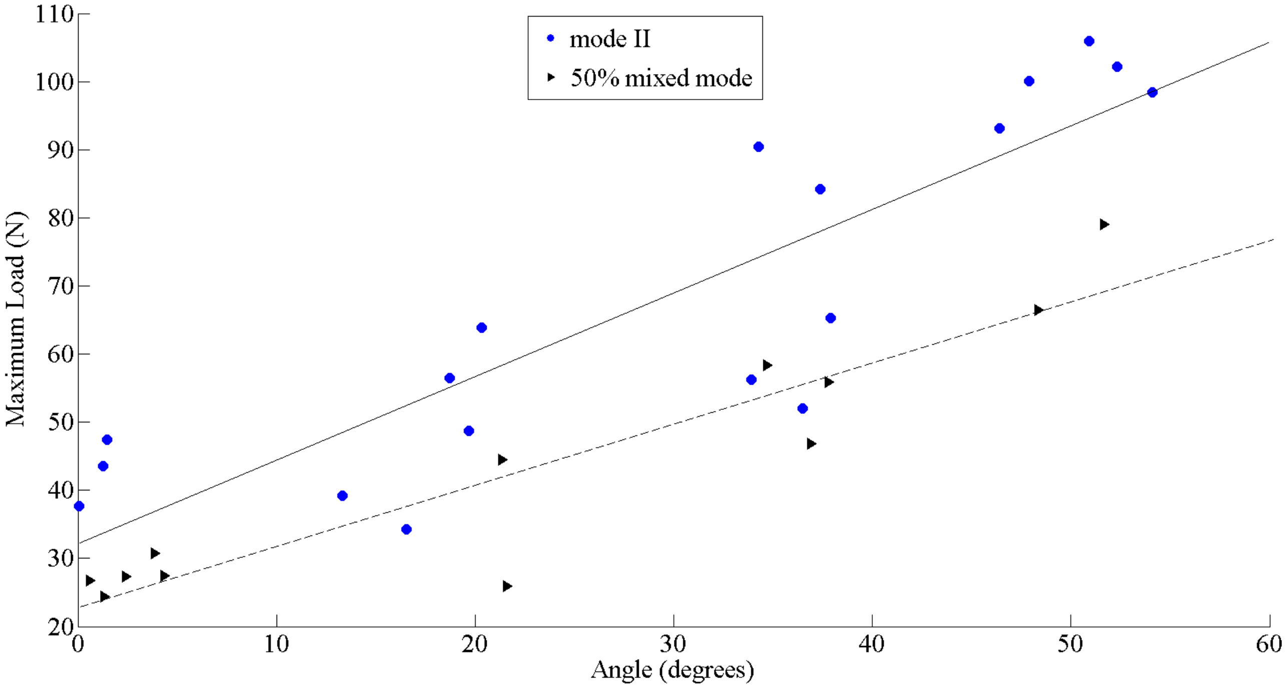


Figure 5 Maximum load vs. insertion angle under mixed and Mode II loading

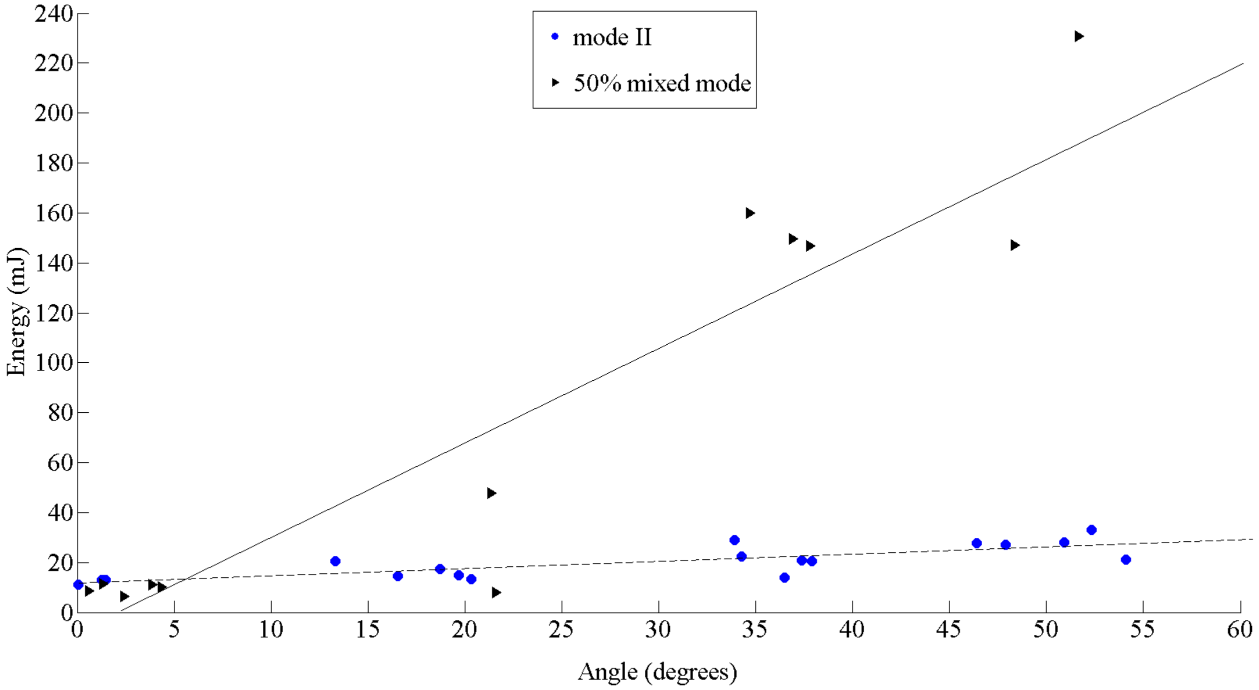


Figure 6 Energy absorption vs. insertion angle under mixed and Mode II loading

The increase in energy absorption and maximum load is due to an increase in axial force P_{axial} acting on the pin as the insertion angle ς increases. Under 50% mixed Mode I/II loading, Z-pins inserted at 30° and 45° are aligned with the load vector. As a result, the typical failure mechanism is pull-out because the frictional forces are dominant. At lower insertion angles, the Z-pins fail by longitudinal splitting and subsequent Z-pin fibre rupture. Similar to the Mode I results, there is a transition region from pull-out to rupture failure as ς decreases which occurs within a range of 23°-33°.

Since the embedded length of the Z-pins increases with insertion angle, the maximum load required for pull-out of Z-pins at larger insertion angles is higher than the corresponding maximum load at low insertion angles. Ergo, under 50% Mixed-Mode I/II loading, the maximum load and energy absorption of Z-pins inserted at 45°, are increased by a factor of $\sqrt{2}$ compared to Z-pins inserted at 0° under Mode I loading. Therefore, for composite structures under mixed Mode I/II loading where the load vectors are well known, inclined Z-pins loaded with the nap are better suited to reduce delaminations compared to conventional aligned Z-pins. Under pure Mode II loading, inclined Z-pins behave like normally aligned pins subjected to Mixed-Mode I/II loading and the corresponding failure mechanisms are the same, i.e. a small amount of pull-out length followed by Z-pin rupture.

4. Conclusions

The study has shown that there is a coherent trend of increasing energy absorption of Z-pins (loaded with the nap) with increasing angle of insertion at high loading Mode mixities. There is a twofold increase in the energy absorption under Mode II loading from increasing the angle of insertion from 0° to 45°. This behaviour is attributed to a rise in axial force acting on the pin as the insertion angle increases. However, inclination of Z-pins is detrimental to the energy absorption under Mode I loading. These findings are particularly useful for design of Z-pinned composite joints where the load vector can be predicted relatively easily.

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