DESIGN DILEMMA FOR Z-PINNED COMPOSITE STRUCTURES

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Abstract

Z-pins are being used increasingly to enhance the delamination toughness and impact damage tolerance of composite aircraft structures. An important consideration in the design of z-pinned structures is the knock-down to the in-plane mechanical properties of the composite material due to the pins. Experimental property data is presented in this paper which reveals that large improvements to the delamination toughness of carbon-epoxy composite gained with z-pins also results in an unavoidable reduction to the in-plane tension, compression, bending, interlaminar shear and fatigue properties. Data shows that increasing the volume fraction of z-pins in carbon-epoxy to raise the delamination resistance causes a corresponding deterioration to the in-plane properties, and this is a key consideration in the design of z-pinned aircraft structures for damage tolerance. The data reveals that the reduction to the in-plane mechanical properties caused by z-pins is usually modest (typically under 5-15%) compared to the very large improvements in delamination toughness (up to nearly 500%).

1 General Introduction

The aerospace industry is seeking low-cost methods to improve the delamination resistance and impact damage tolerance of aircraft structures made using fibre-polymer composite material. Aircraft composite structures are susceptible to delamination damage from bird strike, dropped tools during maintenance, and other impact events. Delamination damage reduces the in-plane structural properties, particularly matrix-controlled properties such as the compression and shear strengths. The aerospace industry has investigated various methods to improve the delamination resistance of composite materials, including toughened resins, thermoplastic film interleaving, fibre surface treatment, and through-thickness reinforcement (e.g. 3D weaving, stitching, *z*-anchoring, tufting). A problem with most methods is they add considerably to the cost and complexity of the manufacturing process for making aircraft composite components. In addition, most methods cannot be readily applied to composite structures made using prepreg materials.

A promising solution is z-pinning, which basically involves embedding high stiffness, high strength rods in the through-thickness direction of the composite [1,2]. Z-pins are thin (under 1 mm in diameter) rods of unidirectional fibre composite, titanium, steel or some other high strength material. The amount of z-pins used to reinforce composites is relatively modest; volume fractions in the range of 0.5% to 5% are used for most applications.

Z-pinning offers the possibility of improving the delamination resistance and impact damage tolerance of aircraft composite structures with only a modest increase in manufacturing cost or, in some circumstances, a cost saving. Partridge et al. [3] in 2003 evaluated the cost and weight savings associated with the z-pinning of composite structural joints. It was estimated that using z-pins as a replacement to titanium fasteners in composite joints can provide a cost saving of over $17,000 and weight saving of 4.5 kg per 1,000 fasteners. It was reported in 2001 that the use of z-pins instead of fasteners in the F-18 E/F Superhornet provides a cost saving of over $80,000 and weight saving of 17 kg per aircraft [4]. The cost and weight savings are achieved by replacing titanium fasteners with z-pins in composite structural joints. In addition to potential cost savings, z-pinning improves the delamination resistance [5-8], low energy impact damage tolerance [9,10], strength properties of bonded joints and connections [11-15], and bearing strength [16,17] of carbon-epoxy. For these reasons, there is growing interest in the design and manufacture of damage tolerant aircraft structures using z-pin technology.

A problem with the z-pinning of composite materials is the reduction to the in-plane mechanical properties, including reduced stiffness, strength and fatigue life [1,2,18-26]. The reductions are caused by microstructural damage to the composite by the z-pins. Damage includes fibre waviness, fibre crimp, resin-rich regions, and swelling which reduces the average fibre volume content. The amount of damage increases with the volume fraction of the z-pins. Consequently, the in-plane properties drop with increasing z-pin content [23-26]. Therefore, designers considering using z-pinned composite materials in aircraft structures face a dilemma: increasing the z-pin content to improve the delamination resistance and impact damage tolerance is accompanied by a reduction to the in-plane mechanical properties.

This paper investigates this dilemma by comparing the improvement to the delamination toughness against the reductions to the in-plane mechanical properties of carbon-epoxy composite material. Using previously published property data [23-26] together with new data, a comprehensive dataset is established to compare increases in delamination toughness against losses in in-plane properties for different carbon-epoxy materials under various loading conditions. The improvement to the mode I delamination toughness of carbon-epoxy with increasing volume fraction of z-pins (up to 4%) is determined. Against this improvement, the deterioration to the in-plane tension, compression, bending, interlaminar shear and fatigue properties with increasing z-pin content is established. The reduction to the in-plane properties is determined for composites with different fibre patterns: unidirectional [0], cross-ply [0/90], quasi-isotropic [0/±45/90] and bias [±45]. The findings of this study can be used by aircraft designers to assess the gains achieved in delamination toughness against the losses in in-plane mechanical performance of composite structures reinforced with z-pins.

2 Experimental Procedure

2.1 Composite Materials

Z-pinned composite specimens were made using carbon-epoxy prepreg. The process used to insert z-pins into composite prepreg involves several stages, which are shown schematically in figure 1. The process begins by placing a foam carrier containing the z-pins over the prepreg stack. The foam carrier is used to ensure an even spacing between the z-pins and to provide them with lateral support during insertion. The z-pins are forced from the foam into the prepreg using a hand-held ultrasonically actuated tool. Pressure applied on the tool by the operator together with compressive ultrasonic waves generated by a transducer inside the tool drive the z-pins into the prepreg. Z-pins were inserted progressively by moving the ultrasonic tool over the foam preform several times until all the pins had fully penetrated the material. After the z-pins are inserted, the foam carrier is discarded and the prepreg is then ready for curing. Chang et al. [23] provide a full description of this process used to z-pin the composite specimens. Chang et al. [13,23] also presents information on the microstructural features of the z-pinned specimens, which included in-plane distortion and out-of-plane crimping of the fibres, resin-rich zones next to the z-pins, and misalignment of the z-pins.

Carbon-epoxy specimens were reinforced with thin (0.28 mm diameter) z-pins to volume fractions of 0.5%, 2% and 4%, which covers the range intended for use in aircraft structures. The z-pins were made of pultruded T300 carbon/bismaleimide with the fibres aligned along the pin axis. The z-pins, known commercially as Z-Fiber, were manufactured by Aztex (Waltham, MA), which now owned by

Albany Engineered Composites. Specimens without pins were manufactured as the control material. Z-pinned and control (unpinned) specimens were produced with unidirectional $[0]_{20}$, cross-ply $[0/90]_{10s}$, quasi-isotropic $[0/\pm45/90]_{5s}$ and bias $[\pm45]_{10s}$ fibre patterns with a nominal thickness of 4 mm for in-plane property testing. Specimens with or without z-pins were manufactured with a $[0/90]_{15s}$ pattern and thickness of 6 mm for delamination toughness testing. The specimens were cured in an autoclave under the conditions specified by the manufacturer of the carbon-epoxy prepreg.

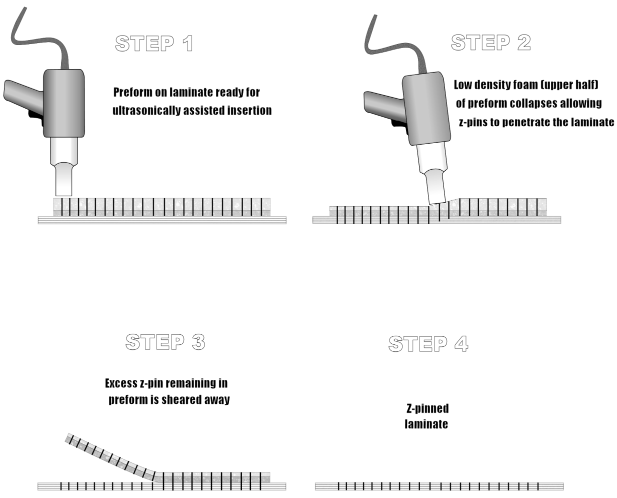


Fig. 1. Major stages in the insertion of z-pins into uncured composite material.

2.2 Mode I Interlaminar Fracture Properties

The mode I interlaminar fracture toughness of the control and z-pinned specimens was measured using the double cantilever beam (DCB) fracture test specified in ASTM D5528 [27]. DCB tests were performed on $[0/90]_s$ specimens that were 120 mm long, 20 mm wide and 6 mm thick. A 25 mm long edge pre-crack at the mid-plane of the specimen was used to initiate the delamination crack, which grew along the two middle [90] plies. The DCB specimens were loaded at a constant crack-opening displacement rate of 1 mm/min using a 50 kN Instron. The delamination was forced to grow in short increments of 5-10 mm, and at each increment the applied force (P), crack-opening displacement (δ) and crack length (a) were measured. Using this information, the mode I strain energy release rate was calculated using [28]:

$$G_I = \frac{3P\delta}{2b(a+\chi h)}\left(\frac{F}{N}\right)$$

where b and h are the width and half-thickness of the specimen, F is a factor to correct for crack length shortening at large displacements, N is a correction factor to account for the stiffening effects of the loading blocks, and the term χh adjusts the measured crack length for compliance of the uncracked part of the specimen. Five DCB specimens were tested for the control material and the composite containing 0.5%, 2% or 4% z-pins.

2.3 Tension Properties

Monotonic and fatigue tension tests were performed in the 0^o fibre direction on the control and z-pinned composites with unidirectional, quasi-isotropic and bias fibre patterns. The specimens were rectangular coupons measuring 200 mm long (100 mm long gauge section), 25 mm wide and nominally 4 mm thick. The entire gauge region of the specimens was z-pinned, with the z-pins aligned in parallel rows along the specimen.

Monotonic load tests were performed using a 250 kN MTS machine at a loading rate of 1 mm/min to measure the tension modulus and ultimate strength. Fatigue tests were performed using the same MTS machine operated under a cyclic load sinusoidal waveform with a stress (R) ratio of 0.6 and loading frequency of 5 Hz. The materials were tested to a range of peak fatigue stress levels between 70% and 95% of the monotonic failure strength to generate fatigue life (S-N) curves. The number of load cycles to failure (N) was taken to be when the specimen can no longer carry the peak fatigue stress, and this coincided with complete fracture. Fatigue tests performed on specimens that did not fail were stopped at one million load cycles. The maximum cyclic stress that the material could withstand without failing after one million cycles was used to determine the fatigue endurance limit. Five samples of the control and z-pinned materials were tested under monotonic loading and one sample of each material for the different fatigue stress levels.

2.4 Compression Properties

The compression properties were measured under monotonic and fatigue loading using the short-block test method. The gauge region of specimen was 25 mm high and 25 wide, and contained a 2.5 mm centre hole. The entire gauge region was reinforced with z-pins aligned in parallel rows along and across the specimen. The compression modulus and strength under monotonic loading was measured by compressing the specimen at a constant rate of 0.5 mm/min until failure. Four specimens were tested of the control material and the different types of z-pinned composite. The fatigue life was measured by applying a cyclic compressive stress to the specimen using a sinusoidal loading waveform. Fatigue tests were performed over a range of maximum stress levels ranging from 75% to 95% of the ultimate compressive strength. The fatigue stress was applied at a frequency of 5 Hz and an *R* ratio of 0.6. The fatigue life was measured by the number of compression load cycles needed to fracture the specimen. The test was stopped if the specimen did not fail after one million load cycles.

2.5 Flexural Properties

Monotonic and fatigue flexure tests were performed on rectangular specimens that were 127 mm long, 25 mm wide and 4 mm thick. The specimens were tested in four-point loading with a support span-to-thickness ratio of 16-to-1 to minimise shear effects. The monotonic tests were performed in accordance to ASTM D790 [29] using a 100 kN MTS machine at a loading rate of 5.3 mm/min. The fatigue tests were performed by cyclically loading the specimens in four-point bending using a support span-to-thickness ratio of 16-to-1. The tests were performed using a cyclic sinusoidal loading condition with a stress (*R*) ratio of 0.6 and loading frequency of 5 Hz. Tests were performed at peak flexural stress levels between 70% and 95% of the flexural strength to generate fatigue life curves.

2.6 Interlaminar Shear Strength

The interlaminar shear strength was determined using the short beam shear test in accordance to ASTM D 5528-94 specifications [30]. The specimens were 40 mm long, 10 mm wide and about 4 mm thick. The specimens were loaded in three-point bending with a support span-to-thickness ratio of 5-to-1, which generated an interlaminar shear stress along the mid-plane. Five samples were tested for each type of z-pinned composite and the control material.

3 Results and Discussion

3.1 Delamination Toughness

The effect of z-pin content on the mode I interlaminar fracture toughness (G_{Ic}) of the carbon-epoxy composite is shown in figure 2. The delamination toughness rises rapidly with the volume fraction of z-pins up to 2%, above which the toughness remains constant (within the bounds of experimental scatter). The large improvement in toughness is due to the z-pins forming a bridging traction zone behind the delamination crack front. The maximum improvement in delamination toughness was nearly 500% at the z-pin content of 2%. Similar or larger improvements to the mode I delamination toughness of carbon-epoxy composites due to z-pinning have been previously reported [5,6,8]. Figure 2 shows that the toughness does not continue to increase above the z-pin content of 2%. This because the arms to the DCB specimens containing 4% z-pins broke before large-scale delamination cracking had occurred (see inset photograph in fig. 2). At the highest z-pin content the delamination fracture load is above the fracture load of the laminate arms to the DCB specimen due to the high toughening effect.

It is worth noting that the maximum mode I delamination toughness achieved by the z-pins (G_{Ic} ~ 7000 kJ/m^2) is higher than that achieved by other toughening techniques such as toughened resins [e.g. 31,32], nano-particle toughen polymers [e.g. 33,34] and thermoplastic interleaving [e.g. 35,36]. This reveals that z-pinning is a remarkably effective method for the delamination toughening of carbon-epoxy materials.

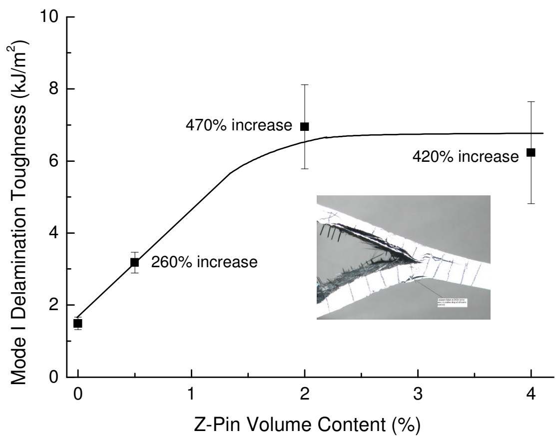


Fig. 2. Effect of percentage volume content of z-pins on the mode I interlaminar toughness.

3.2 In-Plane Elastic Properties

Figure 3 shows the effect of increasing volume fraction of z-pins on the tensile modulus of carbon-epoxy composites with unidirectional [0], quasi-isotropic $[0/\pm45/90]_s$ or bias $[\pm45]_s$ fibre patterns. The elastic modulus of the three composite materials does not change significantly over the range of z-pin contents that were investigated. The average values for the tension modulus appear to drop very slowly with increasing z-pin content, although this reduction is not statistically significant due to the scatter. This agrees with finite element analysis which predicts the elastic properties of carbon-epoxy composites do not drop by more than 5-10% when the volume content of z-pins is under a few percentage [18,19].

To investigate further the stiffness properties of z-pinned composites, the effect of z-pin content on the elastic modulus of different carbon-epoxy under tension, compression and bending loads is presented in figure 4. In this figure the elastic modulus value of the z-pinned composite ($E_{z\text{-}pin}$) is normalised to the control material (E_o) with the same fibre pattern. The modulus values are normalised to allow comparisons between z-pinned materials with different fibre patterns tested under different load conditions. The E_o values for the control carbon-epoxy composites are given in figure 4. Data presented in the figure shows that z-pins have no detrimental effect or reduce slightly (under 15%) the tension, compression and bending moduli. The data also shows there is no obvious correlation between the change to the elastic modulus for the z-pinned composites and their fibre pattern. That is, there is no one type of fibre pattern that experiences a greater reduction to the stiffness properties than the other patterns. Within the bounds of scatter, the changes in elastic modulus for the unidirectional, cross-ply, quasi-isotropic and bias composites are the same. Figure 4 also shows that the change to the elastic modulus is not dependent on the load condition; with the tension, compression and bending moduli showing similar trends with increasing z-pin content.

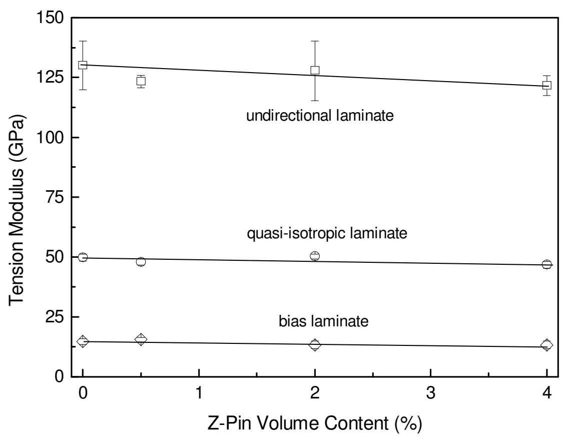


Fig. 3. Effect of z-pin content on the tension modulus of carbon-epoxy.

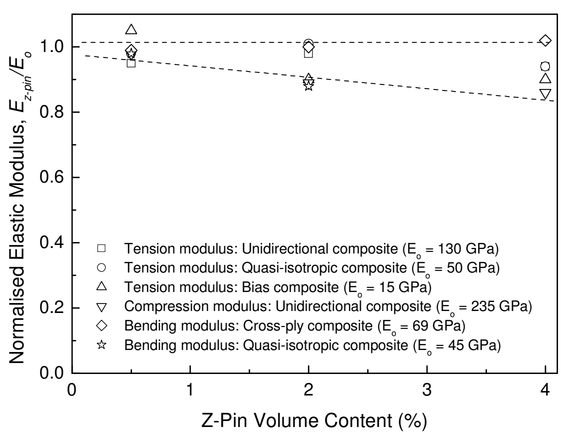
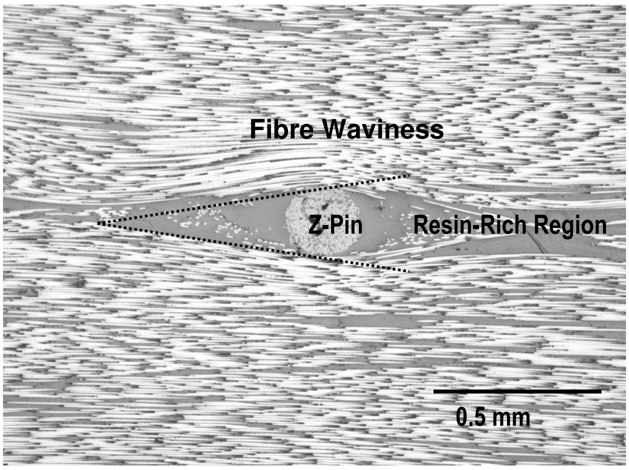


Fig. 4. Effect of z-pin content on the normalised elastic modulus of carbon-epoxy.

The small reduction (under 15%) to the elastic modulus is caused by microstructural changes to the carbon-epoxy induced by the z-pins. The pins cause in-plane fibre waviness and out-of-plane crimping to the carbon fibres in the composite material, as shown in figure 5. The waviness caused by the fibres bending around the z-pins is modest, with the average deflection angle being only 4^{o}. Such a shallow deflection angle, which is confined to a small volume of material surrounding each z-pin, does not have a significant influence on the stiffness properties. The fibres are crimped through a large angle in the through-thickness direction by the z-pins (fig. 5b). But again, only a small volume of material is affected by crimping and therefore the reduction to the bulk stiffness of the composite is small.



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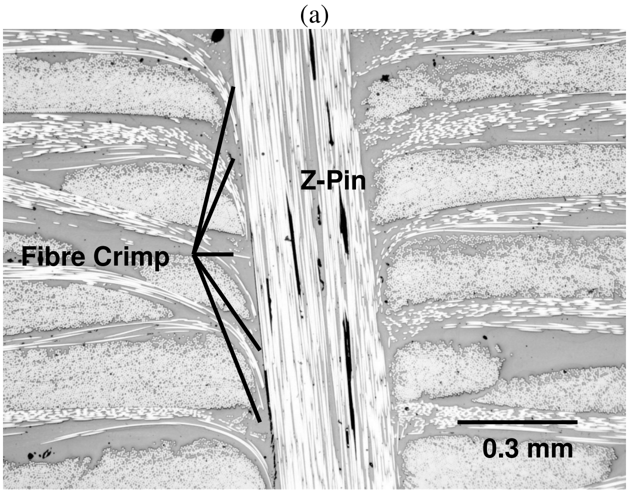


(b)

Fig. 5. (a) Fibre waviness in the in-plane direction caused by z-pins. (b) Fibre crimp in the through-thickness direction caused by z-pins.

3.3 In-Plane Strength Properties

The effect of z-pin content on the tension strength of unidirectional, quasi-isotropic and bias carbon-epoxy materials is shown in figure 6. The average tension strength decreases at a quasi-linear rate with increasing volume fraction of z-pins. However, the rate of strength loss is not the same for the three types of composite material; the average strength decreases at a faster rate for the unidirectional composite (reduction of 270 MPa per 1% increase in z-pin content) compared to the quasi-isotropic and bias materials, which have the same strength loss rate (reduction rate of 60 MPa per 1% z-pins). This reveals that the reduction to the tension strength of z-pinned composites is dependent on their fibre pattern, unlike their Young’s modulus.

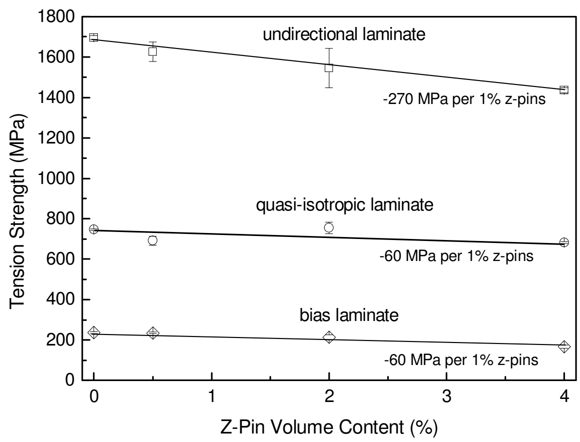


Fig. 6. Effect of z-pin content on the tension strength of carbon-epoxy.

Figure 7 shows the normalised failure strengths for z-pinned composites under tension, compression or bending. The normalised strength is the failure strength of the z-pinned composite ($\sigma_{z\text{-}pin}$) divided by the failure stress of the control material (σ_o) with the same fibre pattern tested under the same load condition. The strength properties show a general decline with increasing volume content of z-pins, although there is significant scatter that increases with the z-pin content. At the highest z-pin content, the average reduction in strength is 20% with the highest strength loss being about 30%.

The reduction to the failure strength due to z-pinning is, on average, more severe than the loss in elastic modulus. The data in figure 7 also shows that the type of load does not significantly influence the percentage reduction in strength. Reductions to the tension, compression and bending strengths caused by the z-pins are approximately the same. Mouritz and colleagues [23-26] examined the failure mechanisms of the z-pinned and control composite specimens under tension, compression or bending. It was found that microstructural damage caused by the z-pins is responsible for the strength loss.

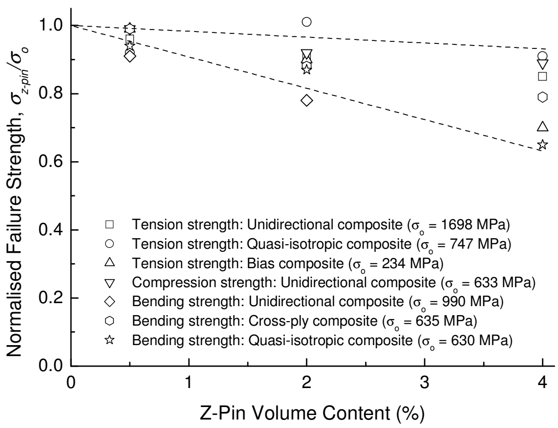
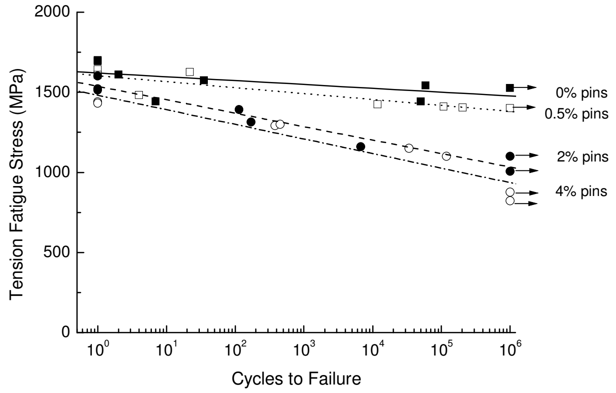


Fig. 7. Effect of z-pin content on the normalised failure strength of carbon-epoxy.

3.4 In-Plane Fatigue Properties

The effect of increasing z-pin content on the tension fatigue life (S-N) curves for unidirectional and quasi-isotropic carbon-epoxy composites are shown in figure 8. Like most carbon-epoxy materials, the unpinned unidirectional and quasi-isotropic composites have a shallow S-N curve which is indicative of high fatigue resistance. The fatigue life of these composites increases rapidly when the tensile fatigue stress is gradually reduced from the static failure stress. The unpinned materials have a high fatigue endurance limit (determined at one million load cycles), which is defined by the maximum cyclic stress the composite can withstand without failing and thereby having an infinite fatigue life. The fatigue endurance stress limit for the unidirectional and quasi-isotropic composites was about 92% and 87% of the static failure stress, respectively.



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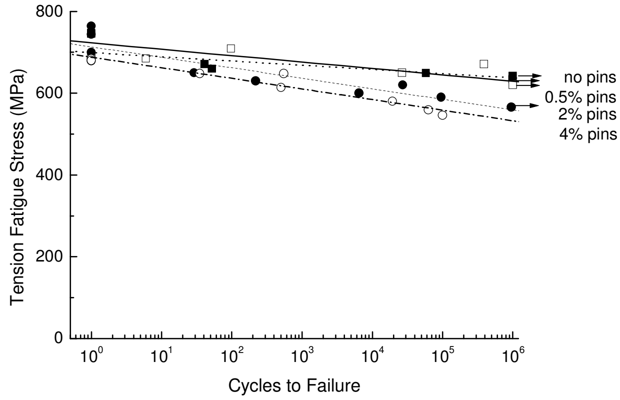


(b)

Fig. 8. Effect of z-pin content on the tension S-N curve of the (a) unidirectional and (b) quasi-isotropic composite. The arrows indicate when the specimens did not fail after one million load cycles (i.e. infinite fatigue life).

The introduction of z-pins into the composites causes a reduction in the tension fatigue performance, with the S-N curves decreasing with increasing volume content of z-pins. The lowest z-pin content (0.5%) caused a small drop to the fatigue life curve for the composites. At the intermediate (2%) and highest (4%) z-pin contents there are much larger reductions to the S-N curves. The fatigue endurance limit for the composites also fell with increasing z-pin content.

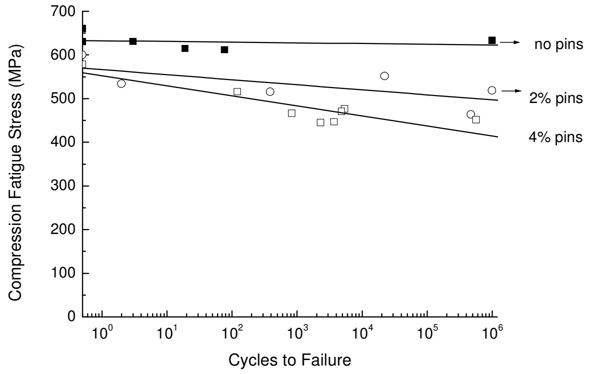
The effect of increasing z-pin content on fatigue life under cyclic compression or bending loading was similar to cyclic tension, as shown in figure 9. The compression fatigue curves were measured for the unidirectional composite and the bending curves for the cross-ply material. Like the tension fatigue behaviour, there is a progressive reduction in the compression and bending S-N curves together with a fall in the fatigue endurance limit with increasing volume content of z-pins. The mechanisms responsible for the reduction to the failure mechanisms of the composites under cyclic tension, compression and bending are reported elsewhere [23-26].

Fatigue endurance limit is an important design property for aircraft structures. The endurance limit combined with appropriate design safety factors is used to determine the maximum operational fatigue stress that can be applied to aircraft materials. Figure 10 shows the effect of increasing volume content of z-pins on the normalised fatigue endurance limit of carbon-epoxy composite with different fibre patterns loaded under cyclic tension, compression or bending. The endurance limit was determined by dividing the endurance stress limit of the z-pinned composite by the endurance limit for the control material without z-pins having the same fibre pattern tested under the same fatigue stress condition. The normalisation of the fatigue endurance limit indicates the change in the maximum operational fatigue stress caused by z-pins.

Figure 10 shows significant scatter in the data, although there is a progressive reduction in the fatigue endurance limit with increasing z-pin content. The lowest z-pin content causes a very small reduction in the fatigue endurance limit, but at 2% and 4% pins the reduction is within the range of 15% to 35%. This reveals that increasing the z-pin content of a carbon-epoxy material to improve delamination resistance will cause a corresponding deterioration in the maximum fatigue stress limit. This reduction occurs regardless of the fibre pattern of the composite or the type of fatigue load.

3.5 Interlaminar Shear Properties

The effect of increasing the volume fraction of z-pins on the apparent interlaminar shear strength of the cross-ply carbon-epoxy composite is shown in figure 11. The strength decreases at a quasi-linear rate with increasing z-pin content, with an average strength loss of 8.5% per 1% increase in z-pins.



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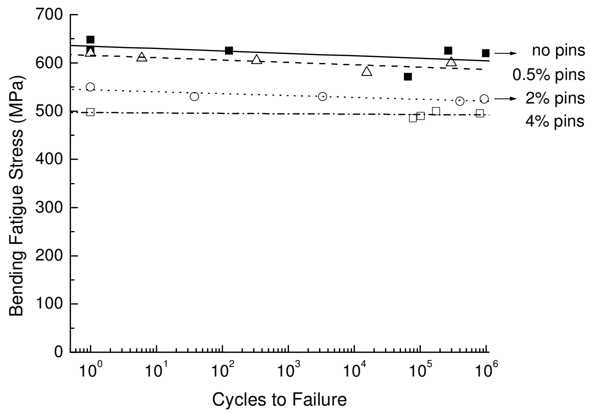

(b)

Fig. 9. Effect of z-pin content on the S-N curve of (a) unidirectional composite under cyclic compression and (b) cross-ply composite under cyclic bending.

The reduction in strength is attributed to a change in the failure mode of the composite caused by the z-pins. Failure of the control material occurred by unstable (fast) growth of a single delamination shear crack along the specimen mid-plane. Failure of the z-pinned composites was more complex involving small-scale delamination cracking along the mid-plane and failure of in-plane fibers. Ultimate failure of the z-pinned composites involved bending-induced rupture, with large-scale interlaminar cracking suppressed by the z-pins. It is well known that z-pins increase the mode II interlaminar toughness by crack bridging and snubbing effects [5,37,38], and this is almost certainly responsible for the restricted interlaminar shear cracking in the z-pinned specimens. With delamination cracking suppressed in these specimens, ultimate failure occurred by bending-induced rupture at the z-pins. For this reason, the strength values for the z-pinned composites given in figure 11 are not actual interlaminar shear strength values (which require the specimen to fail by a single delamination crack along the mid-plane), but a complex strength parameter involving a combination of in-plane shear and bending loads.

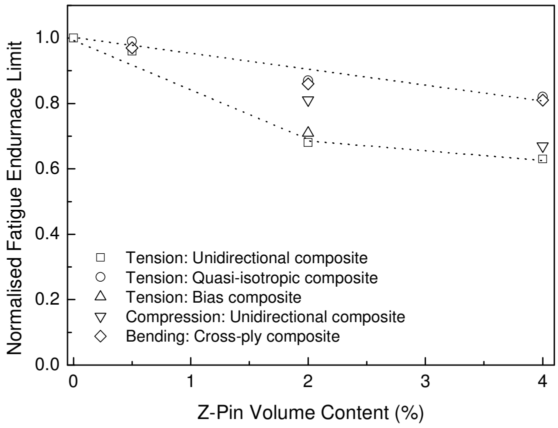

Fig. 10. Effect of z-pin content on normalised fatigue endurance limit of carbon-epoxy.

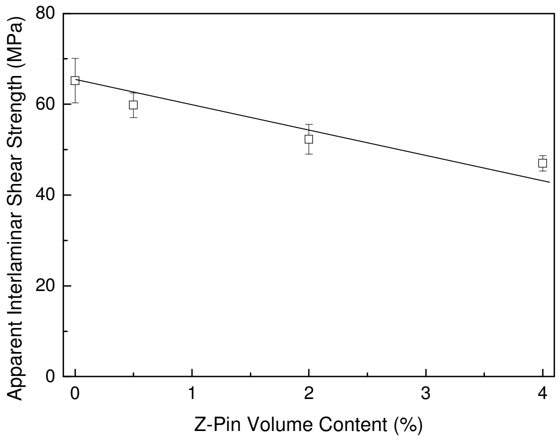

Fig. 11. Effect of z-pin content on the apparent interlaminar shear strength of cross-ply carbon-epoxy.

4 Conclusions

The through-thickness reinforcement of carbon-epoxy composite materials with z-pins to improve the delamination resistance and impact damage tolerance can degrade the in-plane mechanical properties. The mode I interlaminar fracture toughness increases rapidly with the volume fraction of z-pins, with the maximum delamination resistance being nearly 500% higher than the unpinned composite at the relatively modest pin content of 2%. There is an upper limit to the maximum toughening achieved by z-pinning because a condition is reached when the in-plane failure load of the laminate is less than the delamination crack propagation load. At this point, large-scale delamination cracking is suppressed and the material has reached the condition of maximum interlaminar toughness.

Increasing the volume fraction of z-pins to raise the delamination toughness reduces the in-plane stiffness, strength and fatigue properties. The in-plane elastic modulus under tension, compression or bending loads decrease gradually with increasing z-pin content, and stiffness reductions up to 15% occur at the highest pin content of 4%. The loss in stiffness is attributed to microstructural changes caused by the z-pins, in particular in-plane fibre waviness and out-of-plane fibre crimp. The tension, compression, bending and interlaminar shear strengths also fall with increasing z-pin content, with the percentage loss in strength being greater than stiffness. The strengths fall anywhere between 10% and 35% at the highest z-pin content, and the strength loss is caused by microstructural damage to the composite (e.g. waviness, crimp, breakage of fibres) from the pins. The fatigue life (S-N curve) and fatigue endurance limit also drop with increasing z-pin content. The reduction to the in-plane monotonic strength and fatigue properties caused by z-pins occurs regardless of the load condition (i.e. tension, compression, bending), and there is no significant difference in the percentage reduction to the properties for the different load states. The knock-down to the in-plane properties caused by z-pins must be considered in the design of z-pinned aircraft composite structures.

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