Flexural properties of z-pinned laminates

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Abstract

This paper examines the effect of pinning on the flexural properties, fatigue life and failure mechanisms of carbon/epoxy laminates. Five-harness satin weave carbon/epoxy laminates were reinforced in the through-thickness direction with different volume fractions and sizes of fibrous composite pins. Microscopic examination of the laminates before flexural testing revealed that the pins caused considerable damage to the microstructure, including out-of-plane crimping, in-plane distortion and breakage of the fibres and the formation of resin-rich zones around each pin. The pins also caused swelling of the laminate that reduced the fibre volume content. Despite the damage, the pins did not affect the flexural modulus of the laminate. However, increasing the volume content or diameter of the pins caused a steady decline in the flexural strength and fatigue life, which appear to be governed by fiber rupture on the tensile side of the laminate. Property changes are discussed in terms of transitions in the dominant failure mechanisms due to the presence of pins.

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1. Introduction

Fibre–polymer composites reinforced in the through-thickness direction with thin metallic rods or fibrous pins are being used increasingly in damage tolerant structures because of their superior delamination toughness and impact damage resistance [1]. Of the various methods of inserting through-thickness reinforcement, only the insertion of pins is currently compatible with prepreg materials and therefore offers the advantage of the manufacture of commercial quantities via minimal modification of established methods. Pinning is a process that involves inserting thin pins through an uncured polymer laminate or sandwich composite [2–4]. The pins are usually 0.25–1 mm in diameter, and are made of high modulus, high strength materials such as titanium alloy, steel or fibrous composite. Composites only require a low pin content (typically 0.5–5% by volume) to achieve large improvements to their impact damage resistance [5–7], post-impact strength [6–8], in-plane shear strength [9], delamination toughness [6,8,10–14], through-thickness compressive strength [15,16], and joint strength [12,17,18]. These improvements have resulted in pinned composites being used in Formula 1 racing cars, F/A-18 (Superhornet) aircraft, and the Joint Strike Fighter [19]. Despite these applications, many designers of high-performance composite structures are hesitant to adopt pinning technology for several reasons, including the high cost of pins, added cost and complexity in manufacturing, limited information on material durability, and the possible reduction of in-plane mechanical properties. Research has shown that pins degrade the in-plane elastic modulus and, in particular, ultimate strength of laminated composites under tension or compression loading [8,20–24]. Pinning can also lower the tensile fatigue strength and fatigue life of composites [22]. The degradation to the mechanical properties is attributed to dilution of the fibre content caused by swelling of the composite to accommodate the pins [4,22] and microstructural damage to the laminate during insertion of the pins, which can involve...
out-of-plane crimping, in-plane distortion and fracture of fibres as well as formation of resin-rich zones and continuous resin channels [22]. While the diameter and volume content of pins is kept low to minimise swelling and damage, the loss in properties can be significant in certain types of composites (particularly unidirectional laminates), and may hinder their use in some structural applications.

The effect of pinning on the performance of laminated composites in tension and compression has been studied in detail [8,20–22], but not in bending. Many of the aerospace structures that may benefit from the improved impact damage tolerance and joint strength gained by pinning, such as wing and fuselage panels, are subject to static or fluctuating bending stresses during flight. This paper investigates the effect of the volume content and diameter of pins on the flexural modulus, strength and fatigue life of an aerospace-grade carbon/epoxy laminate subjected to monotonic and cyclic flexural loading. The microstructural damage caused by pinning is determined to assess its influence on mechanisms and thence on properties.

2. Materials and experimental techniques

2.1. Fabrication of z-pinned laminates

The flexural test specimens were made using a 5-harness satin carbon/epoxy prepreg. The properties of the prepreg are given in Table 1. The specimens contained twelve plies of prepreg stacked in a [0/90] pattern with the 0° fibres aligned along the specimen length. Prior to curing, the prepreg stack was debulked by vacuum bagging and then reinforced using pultruded carbon/bismaleimide pins. The pins were 8 mm long, and their tips were chamfered to an angle of about 45° to ease their insertion into the prepreg stack. The pinning process begins by placing a foam preform containing the pins over the stack. The pins are arranged in a square pattern inside the foam. The foam is used to ensure an even spacing between the pins and to provide lateral support to the pins during insertion. The pins are driven from the foam into the prepreg using a hand-held ultrasonically actuated horn in a process that is shown schematically in Fig. 1 and described by Freitas et al. [2]. Pressure applied on the horn by the operator together with compressive ultrasonic waves generated by the horn drive the pins into the prepreg. The pins were inserted progressively by moving the ultrasonic horn over the foam preform several times until all the pins had fully penetrated the prepreg stack. The leading tip of the pins protruded slightly from the underside of the prepreg. The excess length was carefully abraded away using fine-grade polishing paper without scratching the surface ply. The pins also protruded from the entry side because they were longer than the thickness of the prepreg stack. The excess length was cut off by shearing the pins along the laminate surface using a sharp blade and then carefully polishing away any remaining pin material. This process of shearing the pins is commonly practised in the manufacture of pinned laminates.

The prepreg was reinforced with thin (0.28 mm) diameter T300/BMI pins to volume contents of 0.5%, 2.0% and 4.0% and with thick (0.51 mm) diameter T650/BMI pins to a volume content of 2.0%. This material matrix allowed investigation of the effect of both pin content and pin size on the flexural properties and fatigue performance. The entire gauge region of the flexural specimens was pinned. The pins were aligned in parallel rows along and across the specimen, as illustrated in Fig. 2. The row spacing between the thin pins was 3.5, 1.75 and 1.2 mm for the volume contents of 0.5%, 2.0% and 4.0%, respectively. The row spacing for the thick pins was 3.2 mm, thus maintaining the volume content of 2.0%.

The prepreg stack was constrained inside a rectangular frame during pinning to suppress lateral spreading of the material. As a result, the thickness of the uncured stack expanded to accommodate the pins. Table 2 gives the final thickness of the cured laminates, and it is seen that the amount of swelling increased with the volume content and diameter of the pins by a percentage greater than the volume percentage of the pins, suggesting that each pin influences in-plane fiber packing over a region significantly larger than the pin itself. The pins may also reduce compaction of the prepreg stack during curing by propping the mould surfaces. The prepreg was consolidated and cured in an autoclave at an overpressure of 500 kPa and temperature of 115 °C for 30 min and then 750 kPa and 180 °C for 1 h.

2.2. Microstructure of z-pinned laminates

The microstructure of the cured laminates was examined using optical and scanning electron microscopy to identify the types of damage caused by the pinning process. The pins were offset at various angles (θ) from the through-thickness direction, as shown by the optical micrograph in Fig. 3. Previous inspection of the pinning process in unidirectional laminates revealed that most of the offset is caused by shearing off the protruding ends of the pins, as described above; with some further rotation arising during pressurised cure [18]. In the present satin weave laminates, the average offset angle was about 10° for the two pin sizes.

Table 1

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ply thickness</td>
<td>0.25 mm</td>
</tr>
<tr>
<td>Tensile strength</td>
<td>47.7 MPa</td>
</tr>
<tr>
<td>Tensile modulus</td>
<td>3.9 GPa</td>
</tr>
<tr>
<td>Tensile failure strain</td>
<td>1.5%</td>
</tr>
<tr>
<td>Compression strength</td>
<td>180 MPa</td>
</tr>
<tr>
<td>Glass transition temperature</td>
<td>190 °C</td>
</tr>
</tbody>
</table>

Data supplied by Hexcel composites.

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1 HexPly® 914 supplied by Hexcel composites.

2 Aztex Inc. (Waltham, MA).
Out-of-plane crimp of the tows occurred in the vicinity of the pins. Crimping was caused by the pin tips pressing into the tows as they penetrated the prepreg stack and by friction dragging fibers along the sides of the pins. The volume of cramped material is only a few percent because it is confined to a small region surrounding each pin. More modest crimp also arises because of the interlacing of tows in the satin weave. Lateral distortion of the fibres also occurred around the pins, causing the formation of resin-rich regions (Fig. 4). The fibre distortion angle (φ) varied considerably depending where the pin was located within the weave structure. The distortion angles ranged between 5° and 25° for both pin sizes, with an average angle of 16°.

The resin-rich regions had a lenticular shape elongated in the fibre tow direction (Fig. 4). These regions can join into continuous resin-rich channels in unidirectional laminates.
when the pins are closely spaced [22], but they are abbreviated in the satin weaves studied here (and in 0/90° laminates studied elsewhere [18]) by orthogonal fibers. Fig. 4 also shows debonding of the z-pin from the surrounding laminate; this cracking is believed to be due to stresses generated by thermal expansion mismatch during the cure process [25].

The pinning process is expected to cause fibre breakage, although this was difficult to detect by microscopy. Fibres were probably broken under the force exerted on the tows by the pins during the pinning process, resulting in clusters of fractured fibres in the vicinity of each pin. The number of broken fibres at the pin locations could not be measured. It is known that only a small number of broken fibres (less than about fifty) clustered together can be a critical defect that reduces the tensile strength of composites.

2.3. Monotonic and fatigue flexure testing

Monotonic and fatigue flexure tests were performed on specimens with the dimensions given in Fig. 2. The specimens were tested in four-point loading with a support span-to-thickness ratio of 16-to-1 to minimise shear effects in the beam specimen. The monotonic tests were performed in accordance to ASTM D790 using a 100 kN MTS machine at a loading rate of 5.3 mm/min. The flexural modulus of the specimen was calculated using:

\[ E_f = \frac{0.17Lm}{bd^2} \]  

where \( L \) is the support span length, \( b \) and \( d \) are the width and thickness of the specimen, and \( m \) is the slope of the tangent to the initial straight-line portion of the load–deflection curve. The flexural strength, \( \sigma_f \), which refers to the local stress on the surfaces of the specimen at failure, is determined by:

\[ \sigma_f = \frac{3P_{\max}L}{4bd^2} \]

where \( P_{\max} \) is the maximum applied load. Only one specimen of each type of laminate was tested under monotonic flexural loading.

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 of the laminate to generate fatigue life (\( S-N \)) curves. Tests were not performed at stress levels below 70% because run-out had been found at 70%. The number of load cycles to failure (\( N \)) was taken to be when the laminate could no longer carry the peak fatigue stress, which coincided with fracture of the specimen. Tests on specimens that did not fail were stopped at one million cycles.

3. Results and discussion

All moduli and strengths in the following were computed using the thickness measured for each individual specimen, to eliminate small variations in thickness from specimen to specimen as a potential source of noise in data trends.

3.1. Flexural properties of z-pinned composite under monotonic loading

Fig. 5 shows the effect of pin content and pin diameter on the flexural modulus. Experimental scatter to the flexural property values is not provided because only one specimen for each type of laminate was tested. However, monotonic tension [22] and compression [26] tests on a significant number of z-pinned carbon/epoxy specimens has shown that the scatter is typically less than 5% of the average property value, and therefore a similar amount of scatter can be expected for the flexural test results. The presence of pins did not cause the elastic flexural modulus to change, despite the swelling and damage caused to the laminate by the pinning process. In-plane distortion and

![Fig. 5. Effect of (a) pin content and (b) pin diameter on flexural modulus.](image)
out-of-plane crimping of the load-bearing fibres around the pins might be expected to reduce the modulus, but the effects apparently do not have a statistically significant effect beyond the knockdown already expected from crimp in the satin weave. The effects of small clusters of broken fibres at each pin are expected to be even smaller. The flexural modulus did not change when the pin diameter was increased at fixed pin volume fraction, consistent with the absence of a dependence on pin content at fixed pin size. The absence of effects on elasticity is consistent with tensile data for carbon/epoxy laminates [22].

The flexural strength dropped at a linear rate with increasing pin diameter at fixed pin volume fraction. For the specimens, the effect of swelling on the strength may be large, because the volume fraction of load-bearing fibres in the laminate was reduced by 4.7% when reinforced with the thin pins and lowered by 8.6% with the thick pins, despite the pin content being the same (see Table 2). Nevertheless, the magnitude of the decrease in strength in Fig. 6 is still greater than implied by the specimen swelling alone, suggesting that damage caused by the pinning process also contributed to the loss in strength. Increasing the pin diameter probably resulted in a greater number of broken fibres at each pin location, although this could not be confirmed by microstructural analysis. The force needed to drive the pins through the laminate increases with their diameter (measured qualitatively by the operator), resulting in a higher stress exerted by the pin tip onto the fibres during the pinning process.

If variations in specimen thickness are not measured but the thickness is assumed to remain that of the unpinned laminate (which is not recommended but has been common in the literature and, in the authors’ experience, in engineering design practice), substantially different bending strengths will be deduced from the critical load (Table 3). The ‘moderated strength’, which is calculated using the thickness of the unpinned material, again declines linearly with pin content, but at a slower rate than if the critical stress is calculated correctly using the thickness of the actual specimen. The trends found here of a linear reduction in flexural strength with increasing pin content and pin size are consistent with those found for the strengths of both unidirectional and quasi-isotropic carbon/epoxy laminates in uniaxial tension [22].

The reduction to the measured flexural strength ($\sigma_f$) with increasing volume content and diameter of the pins can be summarised numerically by the linear equation:

$$\frac{\sigma_f}{\sigma_f^{(0)}} = [1 - xDc_t]$$

where $\sigma_f^{(0)}$ is the flexural strength of the unpinned laminate, $c_t$ and $D$ are the area fraction and diameter of the pins, and $x$ is a material constant determined by curve-fitting to the data, and has a value of 0.22 mm$^{-1}$ for the satin weave laminate. The authors have found that the same linear relationship between strength and the pin content and diameter can be applied to calculate the tensile strength.

![Fig. 6. Effect of (a) pin content and (b) pin diameter on flexural strength.](image-url)
of pinned laminates, but with different values of the constant $a$.

Fig. 7 shows photographs taken after testing of failed specimens with and without pins. In the absence of pins, the laminate failed by bending-induced tensile rupture of the surface ply, which was accompanied by delamination cracking between all plies. Tensile rupture of the surface fibres is deduced to be the first failure event: the flexural stress–strain curves remained linear to ultimate failure, suggesting that delaminations, which would be non-critical on the tensile side, did not form until after the main fracture event. Furthermore, there would be no driving force for delamination on the tensile side of the specimen without prior fibre breakage. The pinned composites also failed by tensile rupture of the surface ply, but delamination was less extensive. The pins suppressed the formation of multiple delamination cracks through the specimen, even at the lowest pin content (0.5%). Pins tend to suppress delamination growth beyond lengths of 1–2 pin rows (or 2–5 mm) by generating bridging tractions that reduce the stress at the crack tip.

Post-mortem examination of broken specimens also revealed that the pinned laminates always failed along a single row of pins (Fig. 8). Some flexural tests were interrupted at stress levels slightly below the expected ultimate failure stress to study failure mechanisms in greater detail. These specimens were pre-loaded to within 80% of the ultimate stress then unloaded to be examined by optical and scanning electron microscopy. Microstructural analysis revealed that cracks leading to complete fracture in subsequent re-loading appeared to initiate in the damaged regions surrounding the pins (Fig. 9). The cracks were confined to the neighbourhood of the specimen surface that experienced tension. They are surmised to have initiated in clusters of broken fibres near the pins, spread radially towards similar cracks propagating from neighbouring pins, and coalesced into a single through-width crack that caused final failure. The deleterious effect on strength of increasing the pin content is probably due to decreases in the proportion of fibers across a section that are unaffected by fiber breakage near pins. It is speculated that the loss in flexural strength can be minimised by staggering the location of the pins in a zig–zag pattern, rather than having the pins located in straight, parallel rows. The zig–zag pattern would increase the spacing between pins across the specimen compared to the straight pattern for a given pin content, possibly resulting in higher strength. However, the effect of the pin pattern on the flexural properties was not studied here, although it is a topic deserving of further investigation.

3.2. Flexural properties of z-pinned composite under cyclic loading

Fatigue life is degraded with increasing pin content and diameter, but this is due mostly to the knock-down in the
static flexural strength caused by the pins (Fig. 10). The unpinned specimens that failed under fatigue loading appeared similar to the specimens without pins that broke under monotonic loading; failure was due to fibre rupture and multiple delamination cracking. Likewise, the failure mode of the pinned laminates under monotonic and fatigue loading was identical, involving rupture across the specimens along a single row of pins with the suppression of multiple delamination cracks. Therefore, the factors that determined the static strength of the pinned laminates, namely fibre dilution and clusters of broken fibres, also controlled the fatigue strength.

The gradients of the $S$–$N$ curves for the unpinned and pinned laminates are virtually identical (Table 4) with the small differences not being statistically significant. The gradient can be used to assess the sensitivity of a material to fatigue-induced damage; an increasing negative value indicates the more rapid accumulation of damage with load cycles. The similar values indicate that the sensitivity of the laminate to fatigue damage is not dependent on the volume content or diameter of the pins, and that the only cause for the reduced fatigue performance is the initial reduction in the static flexural strength caused by the pins.

4. Conclusions

The flexural strength and fatigue life of satin weave carbon/epoxy laminates used in aircraft are lowered by the presence of fibrous pins. However, the flexural modulus is not changed for the range of pin contents and pin sizes studied here; and this is consistent with work by Chang et al. [22] on the tensile modulus of similar pinned carbon/epoxy laminates.

The flexural strength decreases at a linear rate with increasing pin content and pin diameter. These trends are consistent with reductions in the tensile strength due to pinning. The flexural fatigue life also decreases with an increase in the amount and size of pins. Since the slopes of the $S$–$N$ curves are similar in pinned and unpinned laminates, the reduced fatigue life appears to be a direct result of the knockdown in static flexural strength.

The insertion of pins into prepreg laminates causes local damage to the microstructure, including out-of-plane crimping, in-plane distortion and fracture of the fibres and resin-rich regions where the fibres have been pushed aside. The damage cannot be avoided, although it can be minimised by better control of the pin insertion process using robotic devices rather than the manual insertion and cutting of the pins that is the common practice. Damage can also be minimised by reducing the pin diameter, and it is speculated that reinforcement by ultra-fine pins with diameters in the nanometer to micron-size range would cause less damage than the existing sub-millimeter size pins. The pins also cause swelling of the laminate that reduces the fibre volume fraction. The volume of the swelling increases with the volume content and diameter of the pins and significantly exceeds the volume of pins.

Of all the observed types of microstructural damage caused by pin insertion, the most harmful to flexural strength and fatigue life is suggested to be fiber breakage, because the failures always occur on the tensile side of the specimen. Clusters of broken fibres at each pin initiate cracks at the tension surface that ultimately cause complete rupture of laminate. The size of the broken fibre clusters is expected to be proportional to the pin diameter; and therefore the substitution of ultra-fine pins for the relatively

Table 4

<table>
<thead>
<tr>
<th>Z-pin volume content (%)</th>
<th>Z-pin diameter (mm)</th>
<th>Gradient</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>−5.0 ± 2.0</td>
</tr>
<tr>
<td>0.5</td>
<td>0.28</td>
<td>−4.9 ± 1.7</td>
</tr>
<tr>
<td>2.0</td>
<td>0.28</td>
<td>−3.9 ± 0.6</td>
</tr>
<tr>
<td>4.0</td>
<td>0.28</td>
<td>−0.8 ± 0.7</td>
</tr>
<tr>
<td>2.0</td>
<td>0.51</td>
<td>−1.8 ± 0.7</td>
</tr>
</tbody>
</table>

Fig. 10. $S$–$N$ curves for the laminate reinforced with different (a) pin contents and (b) pin diameters. In (a) the laminate was reinforced with the thin (0.28 mm) pins. In (b) the laminate was reinforced to a pin content of 2%.
large pins of current technology is therefore recommended. Staggering the pins in a zig-zag pattern would increase the spacing between pins across the laminate that may possibly increase the fatigue life.

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