# FATIGUE PROPERTIES OF Z-PINNED AIRCRAFT COMPOSITE MATERIALS

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## Abstract

*The effect of z-pinning on the fatigue strength of unidirectional carbon/epoxy composites under cyclic tensile or compressive loading is determined. Experimental testing revealed that z-pinning degrades the elastic modulus, ultimate strength and fatigue strength of composites in tension or compression. The tensile fatigue strength is degraded by damage due to z-pinning, particularly fiber dilution caused by swelling, fiber breakage and resin-rich zones. The reduction to the compressive fatigue strength is attributed to laminate swelling and fiber distortion, which lowers the compressive stress required to cause failure by fiber kinking. Data presented in the paper reveals that the adverse affect of z-pinning on the fatigue strength could be minimized by using very fine pins.*

## 1 General Introduction

Z-pinning is a technology used to enhance the damage tolerance of polymer composite panels and structural joints. Z-pins are thin rods made of high modulus, high strength metal alloy or fibrous composite. The pins are inserted through-the-thickness of composite panels to improve the impact damage resistance and delamination toughness. Pins are also inserted into composite joints to increase the ultimate strength and fatigue endurance. For these reasons, z-pins are used to reinforce carbon/epoxy composite structures on the F/A-18 *Superhornet* and are being considered for the *Joint Strike Fighter*.

A major concern with reinforcing aircraft composite structures with pins is the possible reduction to the in-plane mechanical properties. The properties are reduced by damage caused by pinning, which includes in-plane distortion, out-of-plane crimping and breakage of fibers, resin-rich zones, and dilution of the fiber volume fraction due to swelling of the composite [1,2]. The damage lowers the elastic modulus, ultimate strength and fatigue life of composites under tensile or bending loads [3-6]. The compressive strength is also reduced by pinning [4,7], although the effect of pins on the compressive fatigue properties has not been reported. Primary aircraft structures experience tensile and/or compressive fatigue loads, and therefore the effect of pinning on their fatigue strength must be known.

This paper determines the effect of z-pinning on the fatigue strength of unidirectional carbon/epoxy composites under tensile or compressive cyclic loading. The mechanisms responsible for changes to the fatigue strength due to pinning are determined, and the conditions needed to minimize the impact of z-pins on the fatigue properties are identified.

## 2 Experimental Details

### 2.1 Z-Pinned Composites

Composite specimens were made using a carbon/epoxy prepreg tape (CYCOM970) supplied by Cytec. The specimens contained twenty plies of unidirectional tape that are all aligned in the same direction. The prepreg stack was debulked by vacuum bagging and then z-pinned in the through-thickness direction using pultruded carbon/bismaleimide rods. Chang et al. [5] describes in full the pinning process used to manufacture the specimens. After pinning the prepreg was cured and consolidated in an autoclave at an overpressure of 500 kPa and temperature of 115°C for one hour and then 750 kPa and 180°C for two hours.

Composite specimens were made containing thin (0.28 mm) or thick (0.51 mm) diameter pins to a volume content of 2%. In addition, control specimens without z-pins were manufactured.

The microstructure of the composites was studied using optical and scanning microscopy to identify the damage caused by pinning. The fibers are forced aside to accommodate the pins, as shown in Fig. 1. This causes localized distortion of the fibers, with the misalignment angle ($\theta$) being 4.0 ± 0.5° for the thin pins and 5.4 ± 0.8° for the thick pins. Fig. 1 also shows small resin-rich zones on both sides of the pin. When the pins are spaced closely together the resin zones at neighboring pins coalesce into a continuous resin channel that extends in the fiber direction, as shown in Fig. 2. These resin-rich channels occurred in the pinned specimens containing the thin or thick pins. Another type of damage is out-of-plane crimping of the fibers, which is caused by bending of the fibers under the pressure used to insert the pins. The crimped fibers were confined to a very small volume surrounding each pin. It is expected that a cluster of broken fibers is present at each pin. The fibers are broken under the pressure needed to force the pins through the laminate. Fibers may also be damaged and broken by friction stresses generated as the pins slide into the laminate. The number of fibers broken by z-pinning could not be accurately measured, although it is expected to increase with the pin size because of the higher pressure needed to insert the thicker pins.

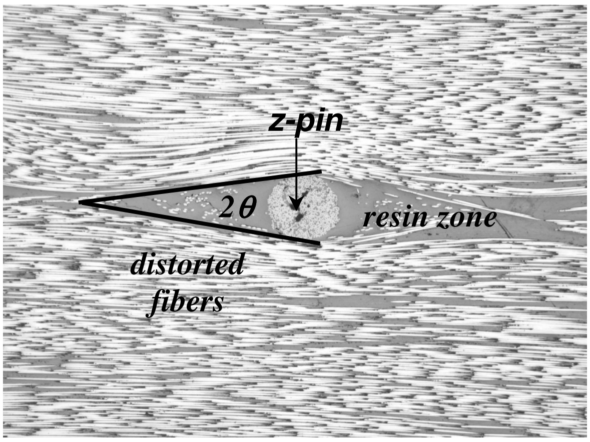



Fig. 1. Local fiber distortion and resin-rich zones surrounding a z-pin.

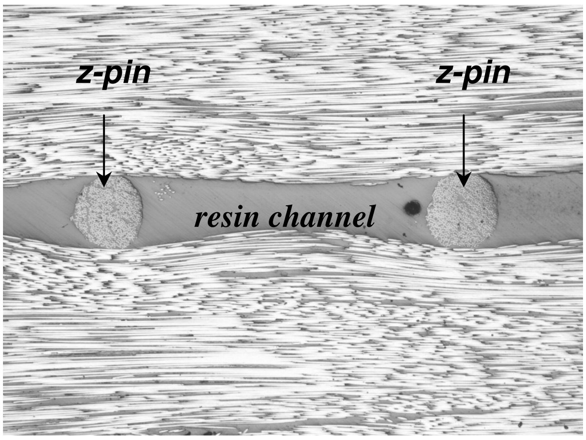



Fig. 2. Continuous resin channel along a row of z-pins.

Z-pinning also caused a small amount swelling which slightly diluted the average fiber volume content. Tables 1 & 2 show the thickness and fiber content of the tensile and compressive composite specimens. The percentage increase in thickness of the tensile specimens is approximately the same as the percentage volume content of the z-pins (2%). This suggests that the swelling is due to the expansion of the composite to accommodate the pins. The swelling is much greater in the compression specimens, and this is attributed to the relatively poor quality control and reproducibility of the pinning process.

Table 1. Tensile composite specimens.

| Composite | Thickness (mm) | Fiber Volume Content |
|---|---|---|
| No pins | 3.94 | 0.600 |
| Thin pins | 4.02 (+2.0%) | 0.588 |
| Thick pins | 4.00 (+1.5%) | 0.591 |

Table 2. Compressive composite specimens.

| Composite | Thickness (mm) | Fiber Volume Content |
|---|---|---|
| No pins | 3.94 | 0.600 |
| Thin pins | 4.36 (+11%) | 0.542 |
| Thick pins | 4.20 (+7%) | 0.563 |

### 2.2 Fatigue Tests

Tension tests were performed using rectangular specimens that were 25 mm wide and 270 mm long. The gauge length was 100 mm, and the entire gauge region was pinned. Compression tests were conducted with open-hole short block specimens. The samples were 25 mm wide with an unsupported gauge length of 25 mm that was completely pinned. The centre of the specimen contained a circular hole with a diameter of 2.5 mm. The pins were arranged in a square pattern with rows of parallel pins aligned in the lengthwise and transverse directions.

The elastic modulus and ultimate strength of the composite specimens was measured in the axial (fiber) direction under monotonic tension or compression at a loading rate of 1 mm/min. Five specimens of each type of composite were tested to determine the average values for the elastic moduli and strengths.

The fatigue life of the composites was measured in the axial direction under cyclic tension or compression. Specimens were fatigued at an R ratio of 0.6 using a sinusoidal load waveform with a frequency of 5 Hz. The number of load cycles to failure was measured over a range of fatigue stress values to generate S-N curves for the composites. Tests were performed using at least five specimens at peak fatigue stress values between 75% and 95% of the ultimate failure stress. Tests were not performed at fatigue stresses below 75% of the ultimate stress because failure did not occur.

## 3 Results and Discussion

### 3.1 Elastic Properties

Fig. 3 shows the effect of z-pin diameter on the elastic moduli of the unidirectional composite. Both modulus show a steady decline with increasing pin size, although the reduction is higher for compression. The compression modulus drops at a linear rate of about 7.5 GPa (or 3.5%) for every 0.1 mm increase in the pin size whereas the tensile modulus decreases more slowly at the quasi-linear rate of 3 GPa (or 2%) per 0.1 mm. The loss in moduli is due to several changes to the material caused by z-pinning. The reduction in the fiber content due to swelling is responsible for a small drop in stiffness. The tensile modulus is expected to decrease by 1.5-2% due to the swelling, although this is less than the total loss in stiffness of the two z-pinned composites. The compressive modulus is also expected to decrease from the swelling. Crimp and distortion of the fibers are expected to contribute to the loss in tensile and compressive moduli. The distortion angle of the fibers, $\theta$, (as shown in Fig. 1) increases with the pin size and this causes a corresponding reduction to the elastic moduli.

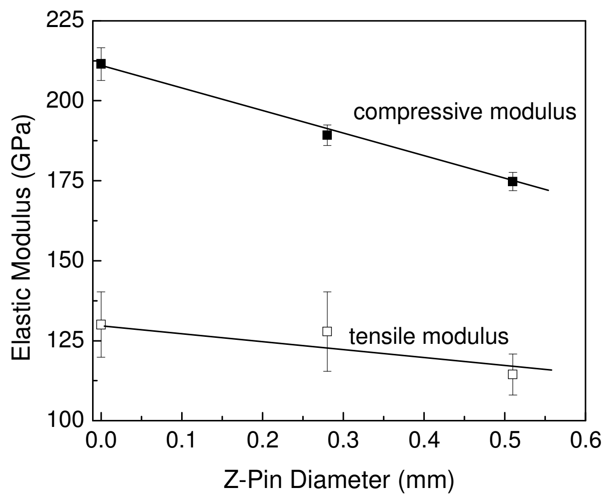



Fig. 3. Effect of z-pin diameter of the tensile and compressive moduli.

## 3.2 Strength Properties

The tensile and compressive strengths of the composite decreased at a linear rate with increasing pin size, as shown in Fig. 4. The strengths drop at a linear rate with increasing pin size, however the tensile strength decreases more rapidly. The tensile strength decreases by about 70 MPa (or 4%) for every 0.1 mm increase in pin size while the compressive strength falls by 17 MPa (or 1%) for every 0.1 mm. This difference can be attributed to different failure mechanisms of the z-pinned composite under tensile or compressive loading.

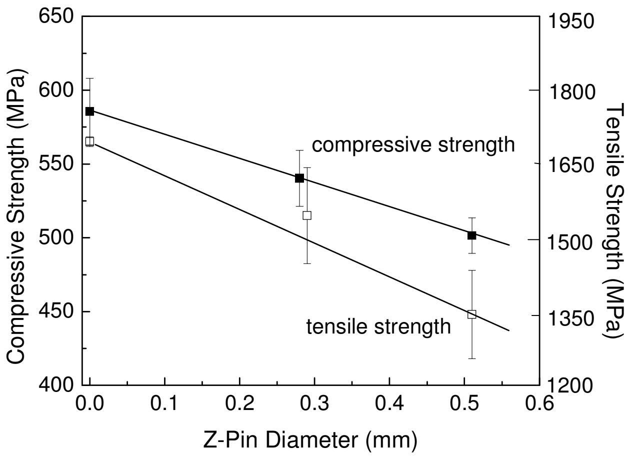
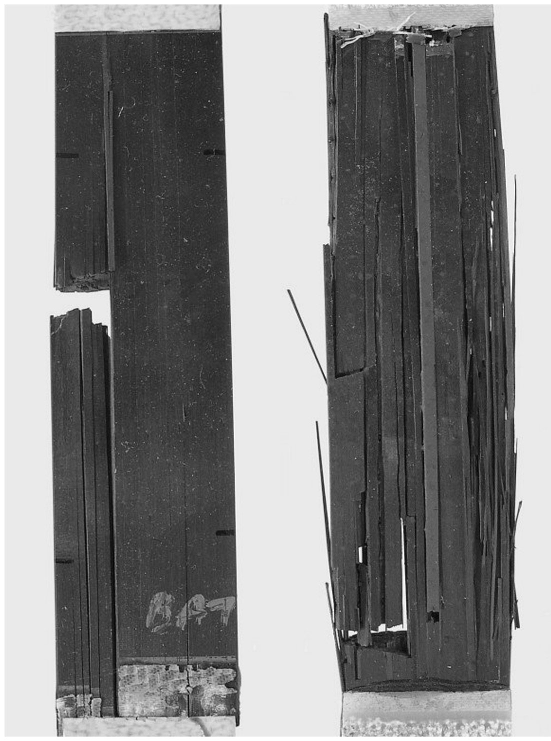



Fig. 4. Effect of z-pin diameter of the tensile and compressive strengths.

Chang et al. [5] studied the tensile failure mechanism in unidirectional carbon/epoxy composites containing z-pins. The composite without pins failed by fiber (ligament) rupture whereas the pinned composite failed by fiber rupture and longitudinal splitting along the axial rows of z-pins, as shown in Fig. 5. Failure of the pinned specimens was sudden and catastrophic, and it is not known whether fiber rupture precedes splitting or visa versa or the two events occur concurrently. Fiber rupture is believed to occur at the cluster of broken filaments near the pins. It is known that a modest number of broken filaments (typically 50-100) clustered in a small volume can initiate tensile failure of unidirectional composites. While the number of broken filaments in the vicinity of the pins could not be measured, it is reasonable to assume that the number is sufficient to create a critical flaw. The size of the broken fiber clusters is expected to increase with the pin diameter because of the greater force needed to insert thicker pins. This accounts for the steady reduction in the tensile strength with increasing pin size.



*No pins* *Pinned*

Fig. 5. Photographs of unpinned and z-pinned composite specimens broken under tensile loading.

The cracks that cause longitudinal splitting of the z-pinned composites were observed using optical microscopy to initiate in the resin-rich zones next to pins. The cracks are nucleated by a transverse tensile strain generated in the resin zone by the partial straightening of the distorted fibers, as shown schematically in Fig. 6. The distorted fibers straighten slightly under the external axial tensile force. Near the ultimate failure stress of the composite the cracks propagate unstably along the resin-rich channels formed along the axial rows of z-pins (as shown in Fig. 2), resulting in the longitudinal splitting. The transverse tensile strain generated by fiber straightening is expected to be greater for the thicker z-pins because the original fiber distortion angle, $\theta$, is higher. Therefore, the applied tensile stress needed to initiate axial splitting will decrease with increasing pin size. This would also account for the reduction in tensile strength with increasing pin diameter. The reduction in the fiber volume content caused by swelling will also make a small contribution to the fall in tensile strength due to z-pinning. However, the fiber dilution is not responsible for the strength decreasing with increasing pin size because the fiber content of the two pinned composites is about the same.

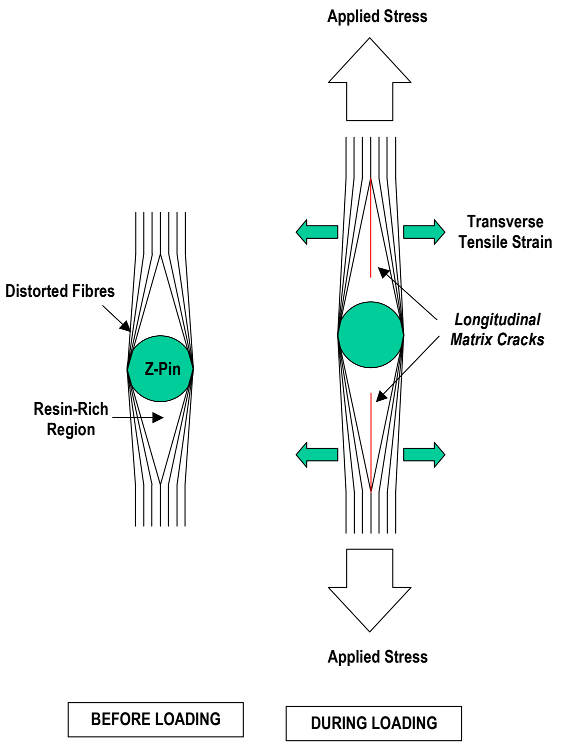



Fig. 6. Schematic of the failure mechanism that causes longitudinal splitting of the z-pinned composites under monotonic tensile loading.

The composites failed under compressive loading by fiber kinking. Failure almost certainly initiated at the edge of the open-hole where the compressive stress is highest. The distortion and crimp of the fibers around the z-pins lowers the compressive stress needed to initiate kinking. Steeves and Fleck [7] observed kink bands close to z-pins in a unidirectional carbon/epoxy composite, and attribute their formation to localized misalignment of the fibers caused by the pins. The compressive kinking stress ($\sigma_k$) of a unidirectional composite is related to the fiber misalignment angle ($\theta$) by the expression:

$$\sigma_k = \frac{\tau_y}{\theta + \gamma_y}$$

where $\tau_y$ and $\gamma_y$ are the shear yield stress and shear yield strain of the material. The fiber misalignment angle increases with the pin size - $4.0 \pm 0.5^o$ for the thin pins and $5.4 \pm 0.8^o$ for the thick pins - and this would account for the reduction in compressive strength with increasing pin diameter. The reduction in the fiber content due to pinning also makes a small contribution to the reduced compressive strength.

## 3.3 Fatigue Properties

Fatigue life (S-N) curves for the composites under cyclic tension or compression loading are shown in Fig. 7. The data shows significant scatter, although it is apparent that all the fatigue life curves are log-linear over the entire range of fatigue stresses. Failure did not occur after one million cycles when the peak fatigue stress was below about 75% of the monotonic failure stress, and the materials are assumed to have an infinite fatigue life.

The tensile and compressive fatigue performance of the composite is degraded by pinning, with the S-N curve shifting the lower stress levels with increasing pin size. Under tensile fatigue loading the reduction to the S-N curve is due in part to the initial knock-down in static tensile strength caused by the pins. However, the tensile S-N curves for the pinned composites decrease at a faster rate (ie. sleeper slope) than the unpinned material due to a more rapid drop in fatigue strength. The tensile S-N curve for the unpinned composite decreases gradually, and only 8% of the fatigue strength is lost after one million cycles. The S-N curves for the composite containing the thin and thick pins decrease more rapidly, and the fatigue strength of both pinned materials is reduced about 35% after one million cycles. This suggests that fatigue-induced damage under cyclic tensile loading accumulates more rapidly in the presence of pins. In comparison, the S-N curves for the unpinned and pinned composites under cyclic compressive loading decrease at a similar rate, and their fatigue strength drops by only 1-2% after one million cycles. This implies that the pins do not cause compressive fatigue damage to build-up more rapidly, and the reduced fatigue performance is due solely to the initial knock-down in static compressive strength.

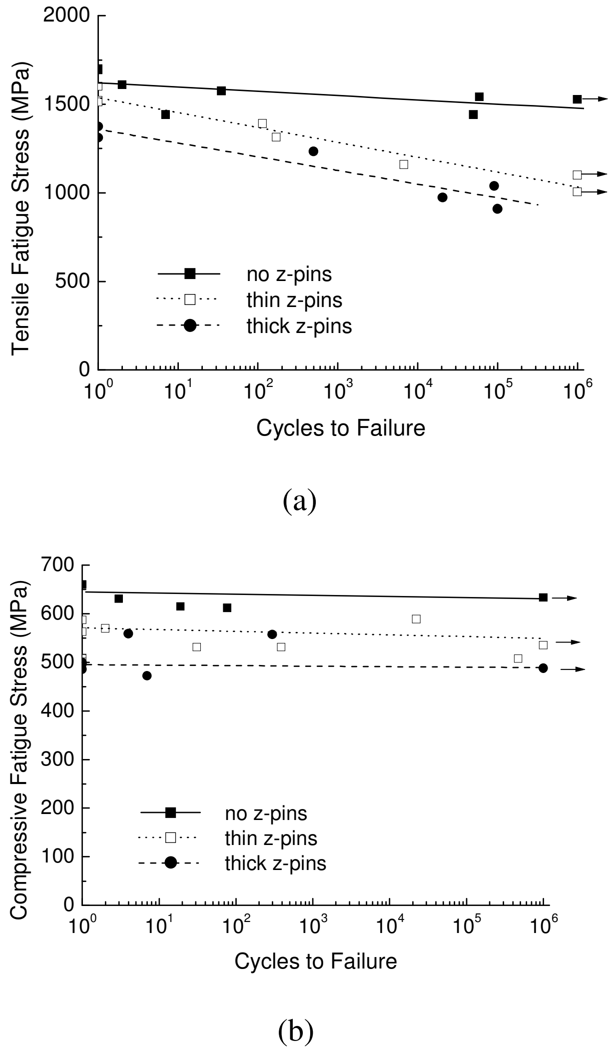



Fig. 7. (a) Tension and (b) compressive fatigue life (S-N) curves.

Post-mortem examination of the broken tensile fatigue specimens revealed the same failure mode as the static tensile samples (Fig. 5). That is, the unpinned composite failed by fiber rupture under cyclic tensile loading whereas the pinned composites failed by fiber rupture and longitudinal splitting. However, the sleeper slope of the tensile S-N curves for the pinned composites implies that substantial cyclic damage occurs around the pins that is not present under monotonic tensile loading. The tensile fatigue mechanism of the pinned composites was not identified by microstructural analysis of the damaged specimens, although it is expected that the mechanism is complex. Based on prior fatigue studies on tape and textile polymer composites [8], it is speculated that under cyclic tensile loading the distorted fibers near the pins debond from the surrounding matrix. A sliding action then develops between the debonded fibers and matrix that causes gradual wearing and attrition of the fibers. The rubbing action weakens the fibers, thereby accelerating the fatigue process. It is also possible that fatigue-induced cracks develop at the clusters of broken fibers near the pins. Cyclic softening and damage to the resin itself, particularly in the resin-rich zones near the pins, may also occur which reduces the fatigue strength and leads to the formation of the splitting cracks. While evidence of the actual tensile fatigue mechanism for the pinned composites is incomplete, it is obvious that pinning degrades the fatigue performance.

The unpinned and pinned composites failed under compressive fatigue loading by fiber kinking. The same fatigue mechanism for the unpinned and pinned materials explains why the S-N curves decrease at the same rate and the compressive fatigue strength is reduced by the same amount after one million cycles. The S-N curve is reduced by pinning because the stress needed to induce fiber kinking is reduced in the presence of pins. It is believed that kinking initiates in the most severely crimped and distorted fibers neighboring the pins. The kinking almost certainly starts at the pins nearest to the edge of the open-hole, where the compressive fatigue stresses are higher than the far-field stress. With increasing number of load cycles the misaligned fibers rotate to greater angles until an unstable kink band is formed near the pins. The initial misalignment angle of the fibers before fatigue loading increases with the pin size, and therefore the kinked fibers must rotate through a shallower angle before an unstable kink band is formed. It is for this reason that the S-N curve decreases with increasing pin size, but the slope of the S-N curves does not change because the fatigue mechanism remains the same.

## 6 Conclusions

Z-pinning is a promising technique for improving the damage tolerance, impact resistance and joint strength of aircraft composite materials. However, the effect of z-pinning on the in-plane mechanical properties must be considered in the safe design of z-pinned aircraft structures. The elastic modulus, ultimate strength and fatigue strength of composite materials is reduced by microstructural damage caused by pinning. The tensile and compressive elastic moduli decrease at a linear rate with increasing pin size. The loss in stiffness is attributed to a reduction to the fiber volume content caused by swelling of the composite to accommodate the pins and the crimping and distortion of the fibers because they are forced to bend around the pins. The fiber distortion angle increases with pin size that results in a greater loss to the elastic moduli. The results show that lowering the pin diameter (while retaining the same pin content) reduces the loss to the elastic moduli. It is speculated that decreasing the pin diameter from the current sub-millimeter size range (0.1-1.0 mm) to the micron or nanometer range will minimize the loss in stiffness. However, the technology for inserting micron sized pins (such as single fibers) or nanometer sized pins (such as nanotubes) into composites at a commercial scale is currently not available.

The tensile and compressive strengths drop at a linear rate with increasing pin size. The tensile strength was reduced by breakage of the fibers during insertion of the pins. The number of broken fibers within a cluster is believed to increase with the pin size, resulting in a greater loss in strength. The tensile strength is also reduced slightly due to the reduction in fiber content caused by swelling, although this is not dependent on the pin size. Tensile failure of the pinned composites was characterized by longitudinal splitting cracks of the resin-rich channels along the rows of pins. It is expected that reducing the pin size to the nanometer or micron scale may reduce the size of the broken fiber clusters and the width of the resin-rich channels, and this could minimize the loss in tensile strength caused by pinning. The reduction to the compressive strength is caused by kinking of the crimped and distorted of the fibers near the pins. The fiber distortion angle increases with the pin size, which in turns lowers the compressive kinking stress. The compressive strength is also reduced by the swelling. Using ultra-fine pins that cause little distortion of the fibers could minimize the loss in compressive strength due to kinking.

Pinning reduces the fatigue strength under cyclic tension or compression, with the loss being more severe under tensile loading. The reduction to the compressive fatigue strength is due to the knockdown in the static compressive strength caused by fiber distortion and swelling. The tensile fatigue strength is reduced by the knockdown in static tensile strength and the rapid accumulation of fatigue-induced damage near the pins. The fatigue life data indicates that using very fine pins can minimize the loss in fatigue performance. Further research into the development of z-pins in the micron to nanometer size range is needed to negate the adverse effects of pinning on the in-plane mechanical properties of unidirectional composite materials.

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