Tensile properties of Z-pinned composite laminates with low damage insertion technique

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Abstract. In this paper, the effects of Z-pin diameter and Z-pin length on the tensile properties of carbon fiber reinforced laminates were studied. A new Z-pin insertion technique which causes less microdamage than the original method was developed. Experimental testing reveals that the in-plane tensile strength of Z-pin specimens is 96.98%-105.32% of the control group. The best performance of in-plane tensile properties is TF18 group which pinned by full-depth Φ0.18mm diameter. The tensile strength increases by 5.32%, and the Young’s modulus increases by 4.71% relative to the control group. Compared with the group of large diameter Z-pin, the in-plane performance of the ultra-fine diameter group is better due to the less in-plane damage. In the half-depth group, delamination occurred between the middle Z-pin sublayer and the upper and lower layers, thus reducing the in-plane tensile property. The Poisson's ratio increases in both full depth and half depth after Z-pinned and it is only related to insertion depth.

1. Introduction

Z-pinning is a mature technique to improve the delamination resistance of fiber reinforced polymer composites [1-6]. It is a process in which a small rod called Z-pin inserts through the thickness direction of the uncured composite, to obtain Z-pinned laminates by curing. Z-pins are generally made of high stiffness and high strength material such as titanium alloy, steel or unidirectional carbon fiber, which are most commonly 0.2mm-1mm in diameters [7-8]. Although the Z-pin volume fraction of laminates is only from 0.5% to 4.0% in general, it is effective at improving the interlaminar strength [9-11], the impact damage resistance and the post-impact properties [12-14] of polymer matrix laminates.

Z-pinning is currently used on the F-18 E/F Superhornet jet fighter and GlobeMaster III heavy-lift transporter [15], and it may be used in other types of military aircraft as well as commercial airliners in the future. Despite those benefits, many designers are reluctant to use Z-pinning on high-performance composite structural parts. The main reason may be that Z-pin can reduce the in-plane mechanical properties of composite laminates. Previous research [16-20] showed that Z-pin degraded the in-plane tensile strength and Young’s modulus properties of the composite laminates. The cause of the phenomenon is that the prepreg is thickened to accommodate the inserted Z-pins, which leads to the reduction of fiber content and microstructural damage during pinning process. The microstructural damage includes fibres breakage, fibre waviness, out-plane fibre crimp and resin-rich zones, etc [21-22].

A.P. Mouritz [2][19] predicted the performance of using ultra-fine Z-pinned laminates based on the tensile strength and modulus as a function of Z-pin diameter. K. Pingkarawat et al. [23] studied the effect...
of embedded Z-pin length on mode I delamination resistance. They found the mode I delamination resistance and the threshold cyclic stress intensity range increase with the increase of Z-pin length. F. Pegorin et al. [24] investigated that both the mode I fracture toughness and fatigue resistance increase with the increase of Z-pin length. The mode II delamination toughness and fatigue resistance increased by Z-pinning, although they didn’t have positive correlation with the length of Z-pin.

At present, most researchers use ultrasonic system to insert Z-pin, which may cause a lot of microscopic damage and influence the in-plane performance of laminates. In terms of Z-pin length, the majority of studies focus on the influence of Z-pin length on the interlayer performance, while the studies on the in-plane tensile properties of Z-pinned laminates influenced by Z-pin length are insufficient. In this paper, a new Z-pinning was used, and extensive tensile tests were carried out about the two research parameters--Z-pin insertion depth and Z-pin diameter. Combined with test results, fracture morphology and curve analysis, the effects of in-plane tensile strength, Young’s modulus and failure mode on toughened composite laminates were investigated.

2. Tensile specimens

2.1 Specimen design

The specimens contained 24 piles of tape stacked in [0/45/0/-45]s pattern. The size of the specimen was 250 mm × 25 mm × 3.6 mm, as shown in Figure 1. A 25 mm × 25 mm square area of intermediate position in the longitudinal direction of specimen was Z-pinned. The row spacing between the Z-pins was 2.5mm.

The depth of Z-pin insertion was divided into full-depth and half-depth. The full-depth means Z-pin through the laminates. The half-depth insertion schematic was shown in Figure 2. Z-pin was located in the middle of the laminate and the length of Z-pin was half the thickness of the laminate.

The diameters of Z-pin were Φ0.28mm and ultra-fine Φ0.18mm. To ensure the accuracy of results, there are 5 test specimens in each group and 25 specimens in total. The specimen parameters were planned as shown in Table 1 below.

| Group | Insertion depth | Z-pin diameter (mm) | Z-pin volume content (%) |
|-------|----------------|---------------------|-------------------------|
| TC    | —              | —                   | —                       |
| TF18  | Full           | Φ0.18               | 0.407                   |
| TF28  | Full           | Φ0.28               | 0.985                   |
| TH18  | Half           | Φ0.18               | 0.204                   |
| TH28  | Half           | Φ0.28               | 0.493                   |

Figure 1. Tensile specimen.  
Figure 2. Schematic diagram of Z-pin half-depth insertion.
2.2 Specimen preparation

The prepreg was made using unidirectional T800 carbon/epoxy tape according to the ASTM
D5687/D5687M-95(2015). Z-pin was made of polyimide fiber impregnated epoxy resin. Inserting Z-pins into the prepreg with special tool.

Traditional Z-pin processes thicken composite laminates, resulting in fiber dilution. Quantification is characterized by a decrease in fiber volume fraction. P. Chang et al. [19] suggest that the laminates thickness increased to accommodate Z-pins and Z-pins are propping mould when cured by conventional curing process. Further studies have shown that the increase in thickness will increase as the diameter of the Z-pin increases. In this paper, by improving the curing process, the thickness of the Z-pinned composite laminates prepared by using the special curing tool did not increase.

![Figure 3. Tensile test specimen with gaps and strain gages.](image1)

![Figure 4. Electro-mechanical Universal Testing Machine.](image2)

To prevent the stress concentration caused by the grips, the aluminum gaps were bonded to the both ends of specimens (Figure 3). There were two BX120-10AA strain gauges on the one side and one BX120-3BA strain gauge on the other side of the specimen. Completed strain gauge calibration according to test standard ASTM E251. The tensile tests were performed in accordance with the ASTM D3039 standard, using a 300 kN Electro-mechanical Universal Testing Machine at a loading rate of 2mm/min and loading frequency of 10 Hz, as shown in Figure 4.

![Figure 5. The load-displacement and stress-strain curves.](image3)

![Figure 6. Control specimen tensile fracture.](image4)
3 Results and discussion

3.1 Test results

The load-displacement and stress-strain curves (Figure 5) are drawn by selecting one specimen for each group. All of these show a linear growth until the final specimen fracture fails. As expected from the test that the curves of the test group and the control group are very similar and almost coincident in load-displacement and stress-strain, which indicates that the pinned laminates by the new Z-pinning avoid serious damage caused by the traditional process.

Figure 6 shows the tensile fracture of the control specimen, and Figure 7 shows the tensile fracture of the Z-pinned specimens with different Z-pin insertion depth and diameter.

According to the ASTM D3039 standard, the tensile failure mode of the control specimen is angled mode fracture occurring in 45° direction. The vast majority of Z-pinned specimens have the same form of failure as controls. Insertion of Z-pins did not alter the failure mode of the composite laminates.

The results were obtained by averaging within the group. The tensile strength, Young’s modulus and Poisson of each group are shown in Table 2 below.

| Group | Tensile Strength Mpa | Increase % | Young’s modulus GPa | Increase % | Poisson’s ratio | Increase % |
|-------|----------------------|------------|---------------------|------------|----------------|------------|
| TC    | 1561.12              | /          | 76.75               | /          | 0.704          | /          |
| TF18  | 1644.10              | 5.32       | 80.36               | 4.71       | 0.711          | 1.85       |
| TF28  | 1616.64              | 3.56       | 80.93               | 5.45       | 0.711          | 3.27       |
| TH18  | 1534.72              | -1.69      | 77.58               | 1.09       | 0.728          | 1.00       |
| TH28  | 1513.96              | -3.02      | 76.36               | -0.50      | 0.727          | 3.41       |

Figure 8 shows the tensile strength and Young’s modulus of specimens with different Z-pin insertion depths. It can be seen intuitively that (1) compared with the control, the tensile strength and Young’s modulus of the Z-pinned composite laminates are not significantly reduced or even increased regardless of the insertion depth; (2) the in-plane tensile properties of full-depth insertion laminates are better than the half-depth. According to the calculation, the tensile strength and the Young’s modulus of the full-
depth insertion laminates are all improved compared with the control group. On average, the tensile strength and Young’s modulus increase by 4.44% and 5.08% respectively.

The bar graph Figure 9 shows the tensile strength and Young’s modulus of each group. The TF28 group tensile strength increases by 3.56% and the Young’s modulus increases by 5.45%. In the fine Z-pin (Ф0.18) full-depth insertion (TF18 group), the tensile strength increases by 5.32% and the Young’s modulus by 4.71%. Both groups of data have achieved excellent results in both strength and modulus. The other two groups show some minor properties loss. Whether in the full-depth or half-depth, fine Z-pin groups performed better than large Z-pin groups in both tensile strength and Young’s modulus.

![Figure 8](image1)

**Figure 8.** The effect of Z-pin insertion depth on the in-plane tensile properties.

![Figure 9](image2)

**Figure 9.** The effect of Z-pin on the in-plane tensile properties.

The effect of Z-pin insertion depth on the Poisson's ratio of the composite laminates is shown in Figure 10. The Poisson's ratio increases in both full depth and half depth after Z-pinned. At full-depth, it increases from 0.704 to 0.711, and the Poisson ratio of half-depth is greater which is 0.727. Figure 11 shows the Poisson's ratio of all specimens. The specific data is listed in Table 2. The Poisson's ratio of the Ф0.18 or Ф0.28 diameter Z-pinned laminates is the same at the same Z-pin insertion depth. Besides, the Poisson's ratio is only related to the Z-pin insertion depth and it is unaffected of the Z-pin diameter.

![Figure 10](image3)

**Figure 10.** The effect of Z-pin insertion depth on the Poisson ratio.

![Figure 11](image4)

**Figure 11.** The Poisson ratio of specimens.

### 3.2 Analysis and discussion
The results of the above Z-pinned composite laminates are striking. A large number of Z-pinned composite laminates tensile tests show that the in-plane tensile properties of Z-pinned composite laminates will be seriously reduced [25]. Nonetheless, further in-depth analysis is necessary. The Z-pin diameter and insertion depth are two key variables studied in this paper. And the test results will be discussed and analyzed in the following combined with the existing published data.

#### 3.2.1 The effect of Z-pin diameter on tensile properties of Z-pinned laminates
If the preliminary analysis is carried out from a macroscopic perspective, the reduction of the in-plane tensile properties of the
composite laminates is inevitably related to the state of the fiber subjected to the load. The cross-sectional area of the specimen is accurately calculated when calculating the tensile strength and the Young’s modulus, which means the influence of the difference between the theoretical and actual cross-sectional areas has been eliminated. Then there are two focus points left. One is the number of fibers carried per unit area, the other is the number of fiber breakage damage. These are the focus of discussion and analysis.

(1) Fiber dilution
Fiber dilution means a decrease in fiber volume fraction. Traditional Z-pen processes thicken composite laminates, resulting in fiber dilution. The presence of resin-rich zones free of reinforce fibers can also lead to fiber dilution. The size of the resin-rich zone is positively correlated with the Z-pin diameter. The larger Z-pin diameter is, the larger area resin-rich zones have.

The thickness of the Z-pinned specimens herein is not changed, and the number of loading fibers are not reduced. The use of fine Z-pin (Φ0.18) reduces the resin-rich zones area. And the Z-pinned specimens do not undergo fiber dilution, which maintains the original fiber carrying capacity.

(2) Fiber breakage
Traditional Ultrasonic insertion brings more fiber breakage[1-3]. When the Z-pins are inserted, the fiber will be destroyed and the number of broken fibers will increase as the Z-pin diameter increases. Previous studies indicate that only a small number of broken fibers (about fifty) clustered together can be a critical defect in reducing the tensile strength of composites [3]. Although it is unclear so far that the correspondence between the number of fibers in the clustered fracture and the Z-pin diameter, it is inferred that when the ultrafine Z-pin diameter is used, as long as the number of clustered broken fibers is less than 50 and the tensile strength can’t be affected. Therefore, the Φ0.18mm diameter Z-pin used in this test may satisfy this condition and thus does not cause a decrease in tensile strength. Further research will be carried out in the follow-up.

(3) Process and other factors
Factors such as process and residual stress also have some effects. After curing, there is residual thermal stress between Z-pin and laminates [9]. And the problem of thermal expansion coefficient matching between Z-pin and composite laminates is also worthy of attention. The fiber direction of the Z-pin is the Z direction, while the fiber direction of the composite laminates is in the in-plane direction, and the thermal expansion coefficients of the two are different, which may result in residual thermal stress. When subjected to tensile load, the combined interface of the two will be a potential damage initiation zone. This is also affected by the size of Z-pin diameter.

In the ultrasonic insertion, when Z-pins are cut by an ultrasonic cutting device, the Z-pin tilt angle and the twist angle will increase, which increases the area of resin-rich zones, the fiber waviness angle and length, the number of fiber breaks, the degree of Z-direction fiber crimp and the residual stress between Z-pin and the laminates after curing. Even in this step, the Z-pin itself may be damaged or the initial defects of Z-pin may be aggravated, such as the Z-pin itself containing voids [1-2].

3.2.2. The effect of Z-pin insertion depth on tensile properties of Z-pinned laminates.
Figure 8 shows that the tensile properties of Z-pinned laminates at half-depth are inferior to full-depth. In fact, from the perspective of microscopic damage, the laminates damage at half-depth must be less than the full-depth. Therefore, there are other factors lead to this result, so it cannot be limited to the microstructure.

![Figure 12. The schematic of layers A, B, C and interfaces X, Y.](image-url)
Briefly, the half-depth Z-pinned composite laminates are composed of three major layers in the thickness direction, as shown in Figure 12. The Z-pins in the layer C may prop layer A and B during curing process, resulting in the potential delamination defects in the interfaces X and Y after curing. The layer C and layers A and B have different thermal expansion coefficients of respective materials, therefore it is easy to generate residual stress at interfaces X and Y. When loading, the Z-pin has support resistance to the layers A and B, which leads to easy delamination at the interfaces X and Y. The wavy fibers in layer C will have a lateral movement that tends to collimate when loaded, which will create shear stress at interfaces X and Y. At the same time, the lateral deformation of layer C is greater than that of layers A and B, so it is easy to delaminate at interfaces X and Y.

Based on the above analysis, it can be found that they all point to the macro defect of delamination. Compared with microstructural damage, the delamination defect plays a leading role. The results of existing tests are produced by the combination of microscopic and macroscopic structure damage.

4 Conclusions

In this paper, Z-pinned composite laminates were prepared by using the new low damage. New Z-pinning insertion technique and the experimental about in-plane tensile properties were studied. On the basis of a large number of experiments, the influence of ultra-fine Z-pin diameter (Φ0.18mm) and insertion depth on in-plane tensile properties of Z-pinned composite laminates was analyzed and discussed. The research presented here has completed the knowledge gap on the effect of the Z-pin insertion depth on tensile properties of z-pinned laminates. Here are the main conclusions obtained:

(1) The new low damage Z-pinning insertion technology does not change the thickness or tensile failure mode of the laminates.

(2) Ultra-fine diameter (Φ0.18mm) Z-pinned laminates perform better in-plane tensile properties. The TF18 group has the best in-plane tensile properties, whose tensile strength increases by 5.32%, and the Young’s modulus increases by 4.71%.

(3) Increase of the Poisson’s ratio by Z-pin insertion, which is only related to insertion depth.

(4) The in-plane tensile properties of full-depth insertion laminates are better than the half-depth. The delamination defect could result in the in-plane tensile properties of half-depth Z-pinned laminates are inferior to full-depth.

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