EXPERIMENTAL STUDY ON THE PERFORMANCE OF TWISTED FIBER REINFORCED COMPOSITE Z-PIN

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ABSTRACT

The poor interlaminar bonding of laminates has been a longstanding problem for composites. One of the promising solution is the emerging 3D reinforcement, Z-pin technology. Z-pins improve the delamination resistance through co-curing bonding with all layers. Z-pin/laminate bonding is the key factor for Z-pin reinforcement effectiveness. In this paper, the concept of twisted fiber reinforced composite Z-pin (TFRC Z-pin) was brought up. The work conducted an experimental investigation on the effect of twist degree of fiber bundle on the bonding force, tensile properties and compressive behaviour. Results showed that the peak bonding load increases with the increase of twist degree with a range of 0-80 twist/m. However, the tensile strength, tensile modulus and critical buckling length decrease. Compared to regular Z-pin, 80 twist/m TFRC Z-pin obtained 19.4% improvement of peak pullout load and 11% decrease of tensile strength. The critical buckling length decreases from 27.2 to 15.6 mm. When the 100 twist/m was used, failure mode of Z-pin changed from pullout to fracture.

1 INTRODUCTION

In the past 20 years, composites have become the most popular materials for light-weight structures, which are usually used in the form of stacked layers with a high risk of delamination and debond. Several 3-dimensional reinforcement techniques were developed to address this problem such as 3D woven, braiding, stitching, and Z-pinning, among which Z-pinning is a promising one especially suitable for prepreg based composite. Z-pinning can dramatically improve the properties related to the through-thickness direction, including the interlaminar toughness, impact resistance and joint strength, by generating the crack closure force between delaminated sublayers[1]. Theoretical works demonstrated that the closure force is mainly determined by the adhesive strength between Z-pin and the laminate while the energy absorption is large contributed by the frictional effects at Z-pin/laminates interface[2].

Research showed that Z-pin factors like the length, diameter, angle and surface characteristics can influence the reinforcing effects[3]. Scholars reported strategies to enhance the reinforcement of Z-pins. Higher mode I interlaminar toughness was enabled by employing a rectangular cross-sectional shape rather than the traditional circular one due to the larger contact surface area at a fixed density[4]. Cryogenic and plasma surface treatment methods were used to form an irregular etched surface with different active chemical groups. Z-pins being treated by oxygen-containing plasma showed stronger bond strength with the laminates and consequently enabled the laminates higher interlaminar crack resistance[5]. Wang et al[6] improved the interfacial adhesion of Z-pins by about 30% through carbon fiber powder coated Z-pins. On the other hand, twisted Z-pins were manufactured by torqueing the Z-pin in a state of partially-cured[7]. Even though 61% increase were tested with the interfacial adhesion, nearly half of the tensile performance were degraded. And the feasibility of inserting the twisted Z-pins through prepregs is questionable. The objectives of this paper is to manufacture Z-pins with higher bonding strength with laminates through the usage of twisted fiber tow and experimentally assess the behaviour of the twisted fiber reinforced composite Z-pins (TFRC Z-pin).

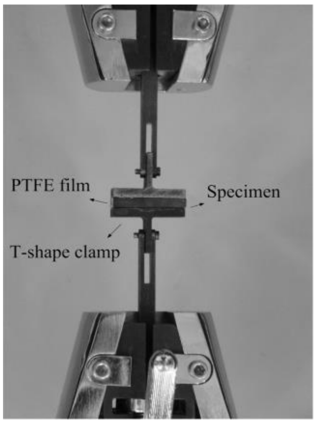
2 EXPERIMENTAL

2.1 Materials

The reinforcement of Z-pins was 1K T300 carbon fiber tow supplied by Toray Industries, Inc. FW125 expoxy resin was used for the matrix supplied by Kunshan YUBO composite materials Co., Ltd the curing temperature of which is 180℃. The lamiantes used in this study were made from USN12500 prepregs offered by Weihai Guangwei Composites Co., Ltd.

2.2 Test methods

Z-pin plays a key role in the interlaminar reinforcement mechanism by generating bridging force between the cracked sub laminates. Theoretical analysis showed that the reinforcement efficacy depends on the Z-pin elastic properties, pin/laminate interfacial adhesive bonding and the frictional effect after debonding. A pullout test method developed by Dai et al.[8] was employed to evaluate the bridging effect of Z-pin herein as shown in Fig. 2. The $20\times40mm^2$ square specimen consists of two 2.5mm $[0/90]_{5s}$ laminates separated by a PTFE film and nine Z-pins distributed in a 3×3 array pattern. As shown in Figure 3, a perforated metal plate was employed to guide the alignment of Z-pins. The stacked prepregs were heated to 60℃ to decrease the insertion resistance. The specimen was glued to the T-shaped fixtures which were connected with the grips. The upper grip moved at a rate of 0.5mm/min to generate pullout load. As a result, the peak load was automatically recorded.



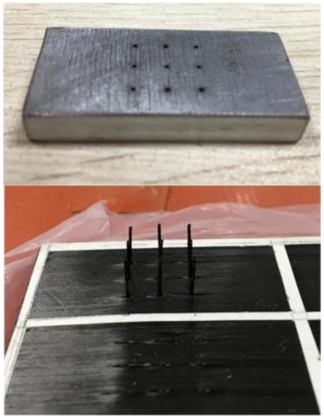


Fig. 2 Z-pin pullout test fixture   Figure 3 Z-pin pullout test specimen

The alignment of reinforced fibers is key factor for the axial properties of the composites rod. Tensile tests as depicted in Fig. 4 were conducted to investigate the degradation of fiber twisting on the tensile strength and modulus of Z-pins. The extensometer was carefully mounted on the specimen for the modulus measurement.

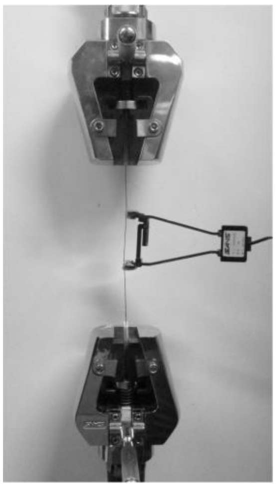


Fig. 4 Fixture of Z-pin tensile test

Given the reduced stiffness of Z-pin, the insertion becomes problematic. Due to the large length-diameter ratio, the slender Z-pin is apt to buckle being applied compression during insertion. Especially, along with the proceeding of insertion, the resistance becoming larger and larger, and as a result, the higher pressure will be needed. The buckling behavior of Z-pin was explored by compressive test. As shown in Fig. 5, a thick plate with Ø0.5mm hole was employed to mimic the base support of prepregs during insertion.

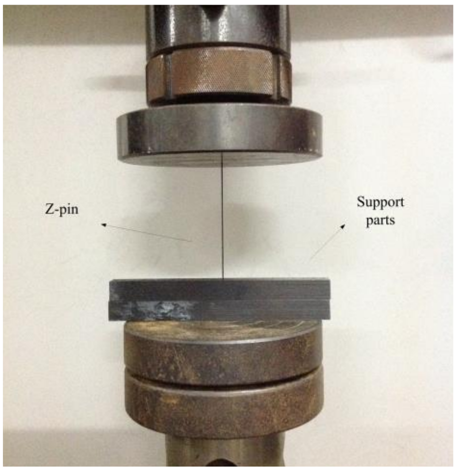


Fig. 5 Z-pin compression test

3 Manufacturing of TFRC Z-pin

As depicted in Figure 6, the pultrusion process TFRC Z-pin involves a rotational movement of the filament. The rotation speed ω (circle/min) depends on the pultrusion speed v_p (m/min) as,

$$w = v_p \times N_t \tag{1}$$

Where the N_f is the twisted degree, twist/m.

In this study, v_p is equal to 3.2mm/min. The temperatures for the resin bath, mould and curing oven were 50°C, 90°C and 180°C respectively. Six types of twisted fiber reinforced Z-pin were pultruded while the carbon fiber bundles were twisted with 0 twist/m, 20 twist/m, 40 twist/m, 60 twist/m, 80 twist/m and 100 twist/m.

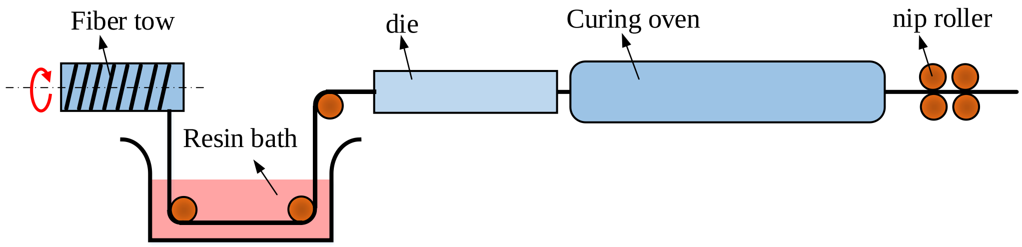


Fig. 6 Pultrusion process of TFRC Z-pin

The appearance of TFRC Z-pins was observed under Leica DVM5000 digital microscope as shown in Fig. 7. It can be clearly observed that helical grooves existed along the outside surface of the twisted fiber tow. Along with the increase of twist degree, the helical angle increases. At lower twist degree, the surface of Z-pin was covered with a layer of smooth resin. When the twist degree becomes higher than 40 twist/m, small resin particles appear around the surface.

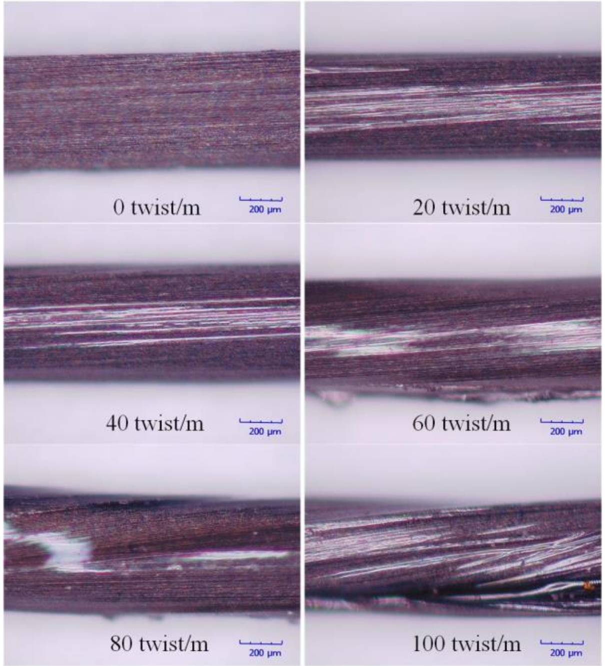


Fig. 7 Appearance of TFRC Z-pin with different twist degrees

4 RESULTS AND DISCUSSION

4.1 Maximum bonding force

The typical load-displacement curve is plotted in Fig. 8 for the regular Z-pin (0 twist/m) and TFRC Z-pin (80 twist/m). As the curve showed, Z-pin experienced three stages before being completely pulled out, including, a) elastic deformation; b) debonding from laminates when the interfacial shear stress limit was reached; c) gradually pullout when the bridging force was balanced by the frictional force. Compared the regular Z-pin, the TFRC Z-pins exhibit both higher peak load and higher residual friction force. The main reason for that is can be explained by the special surface appearance of Z-pin discussed before. The grooves around the twisted Z-pin will be filled with resin from the laminates during the cure. On one hand, the grooved surface enlarged the contact surface between Z-pin and laminates; on the other hand, the resin diffusion from laminates into Z-pin surface lead to a more rough fracture surface of the debonded Z-pin. The averaged influencing of the twist degree of Z-pin on the peak load was summarized in Fig. 9.

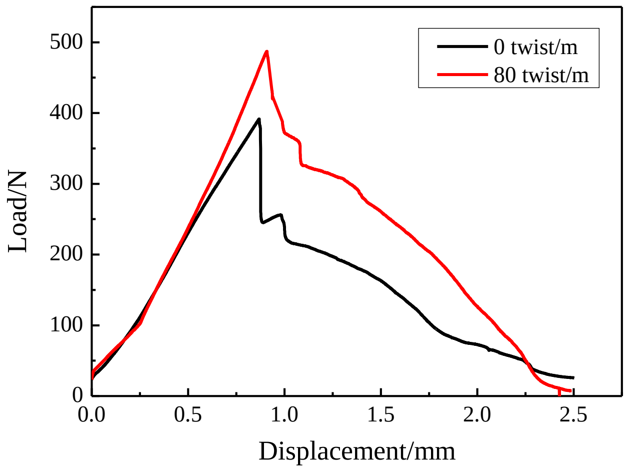


Fig. 8 The load-displacement curve of pullout test

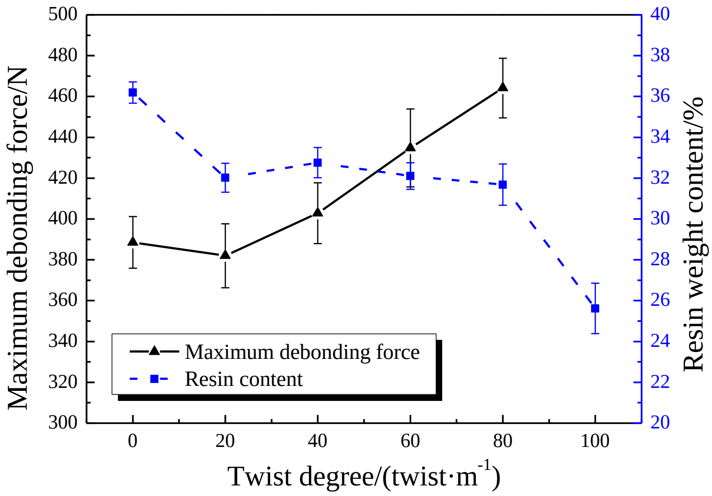


Fig. 9 Maximum debonding force of TFRC Z-pins with different twist degree

Seen from the results, the maximum debonding force increases with the twist of the carbon fiber with a range of 20-80n/m. Compared to non-twisted fiber reinforced Z-pin, the maximum debonding forced is improved by 19.4% by 80n/m twisted fiber. The resin content was also measured for different groups of Z-pin. It shows that the resin content decreases along with the increase of twist degree. We didn't obtain the debonding load for 100 twist/m Z-pin because Z-pin failed by rupture rather than pullout which infers degraded axial strength of Z-pins induced by the twists in fiber tow.

4.2 Tensile properties

The tested tensile strength and modulus were plotted in Fig. 10. Both tensile strength and modulus manifest continuously reduction along with the increase of the degree of fiber tow distortion. For the group with highest maximum bonding force (80n/m), the reduction of tensile strength and module decreased 14.1% and 11.0%.

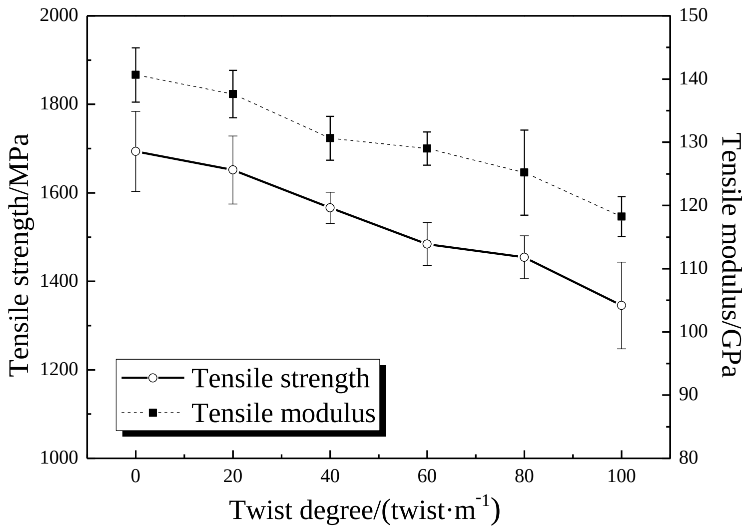


Fig. 10 Tensile strength and module vs. the twist number of Z-pin

According to the spiral morphology of the twisted fiber bundle, the helical angle θ depends on the twist degree as,

$$\theta = \tan^{-1}[\pi(D-d)N_t] \quad (2)$$

Where D and d is the diameter of the fiber bundle and fiber respectively. With the same die inner shape, both of them are constant. For 100 twist/m Z-pin, the helical angle is equal to 9° which leads to a certain amount of loss of axial properties. As a result, it fails by fracture rather than debonding during the bridging the opened crack.

4.3 Critical buckling length

When imposed on compression, Z-pin tend to buckle due to the fine diameter. The destabilization can prevents the insertion. The critical buckle length of Z-pin determines the maximum depth of Z-pin insertion, consequently deciding the thickness of laminates to be reinforced by Z-pins. The compressive test results were listed in Table 1.

Twist degree [twist/m]	0	20	40	60	80
Critical length [mm]	28	26	20	22	12
	32	26	22	18	16
	26	30	22	18	14
	26	28	26	20	18
	24	24	18	22	18
Average[mm]	27.2	26.8	21.6	20.0	15.6
CV [%]	3.03	2.28	2.97	2.00	2.61

Table. 1 The critical buckling length of TFRC Z-pins

Results reveal a reduction of critical buckling length of Z-pin along with the increase of twist number. Tensile test results have demonstrated that the axial stiffness is degraded by the twisting of fiber tow which mainly account for the buckling length decrease. For 80n/m twisted fiber reinforced Z-pins, the maximum insertion depth is 15.6mm within the current used insertion methods.

5 CONCLUSIONS

In this paper, we manufactured twisted fiber reinforced Z-pins through pultrusion process and conducted a comprehensive evaluation on the performance of Z-pins with different twist degrees. The microscopic examination revealed that there exists helical grooves on the surface of TFRC Z-pin. The enlarged contact area between Z-pin and the laminate imparts an improvement on the maximum bridging load generated by Z-pin. Compared to the regular Z-pin, 80 twist/m TFRC Z-pin achieves 19.4% increase of peak debonding load. However, along with the increase of twist degree, the tensile strength and module decrease. As a result, when the twist degree is up to 100 twist/m, the TFRC Z-pin fails by rupture rather than debond under pullout load. Also, the critical buckling length of Z-pin decrease with the increase of the twist degree.

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