Research Article

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Delamination properties and *in situ* damage monitoring of z-pinned carbon fiber/epoxy composites

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Abstract: Carbon-fiber-reinforced composites with layer stacking structures are sensitive to delamination crack. To improve the interlaminar properties and further explore the capability of *in situ* damage monitoring of the laminate, CCF300 and CCF800 carbon fiber pins were selected to fabricate the z-pinned composites. Compared with the control sample, the G_{IC} values of CCF300 and CCF800 z-pinned composites are increased by 398 and 378%, respectively. This indicates that the delamination resistance improvement of the laminates is dominated by the z-pin debonding and pull-outs. The electrical resistance of the laminates was utilized to *in situ* monitor the crack propagation within the composite laminate. The results show that the presence of the z-pins enhances the sensitivity

of damage detection. The $\Delta R/R_0$ of CCF800 z-pinned composite is nearly three times that of the control sample at the moment the crack length reaches 110 mm. Crack length–displacement curves were obtained according to the relationship between ΔR and Δa , which clearly displayed the steady or stick-slip crack growth of the laminates with or without z-pins, respectively. Visualization of the crack growth process can provide a novel method for the delamination failure analysis of the composite.

Keywords: z-pin composite, interlaminar fracture toughness, *in situ* damage monitoring

1 Introduction

Carbon-fiber-reinforced composites exhibit high specific strength and modulus, designability of ply direction and shape, and are suitable for integral molding [1,2]. However, composite laminates are sensitive to delamination crack [3] due to the layer-by-layer stacking structure. Various techniques such as stitching [4], 3D braiding [5,6], and z-pining methods improved the interlaminar properties and have aroused extensive interest. Although the z-pins result in an unavoidable reduction in the in-plane elastic modulus [7], tension [8], compression [9], bending [10], and fatigue performance [11], the reduction in the in-plane mechanical properties caused by z-pins is usually modest (5–30%) in contrast to the very large improvements in interlaminar fracture toughness (above 400%) [12]. Therefore, z-pinning has attracted extensive attention [13,14] as an interlaminar reinforcement method. The bridging effect of z-pin plays an important role in the interlaminar fracture toughness improvement [15]. In z-pinned composite laminate, crack growth is prevented through the interaction between z-pins and the surrounding laminates. The pullout of z-pins from the laminate consumes a large amount of energy [16], resulting in the improvement of fracture toughness. The influences of the z-pin volume content [17–20], z-pin diameter [21,22]

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and z-pin angle [23,24] on the improvement to the G_{IC} of the composites have been extensively researched. For the z-pin properties, Pingkarawat and Mouritz [25] made z-pins from copper, steel, and carbon fiber to enhance the interlaminar fracture toughness of laminated plate. Their work proves that the carbon fiber is the most effective reinforcement material. However, the effect of the carbon fiber properties on the G_{IC} of the composites needs further exploration.

At present, academics and industry are not only satisfied with improving delamination resistance of carbon-fiber-reinforced composites but also interested in detecting the crack initiation within the laminates during the service period. Once the crack is initiated, the delamination will expand rapidly until the structure fails [26,27]. Acoustic emission and c-scan have been used in nondestructive testing for polymer composites [28,29]. However, neither the c-scan nor acoustic emission method can quantitatively analyze the structure and processing quality of the z-pinned composites. Due to the conductivity of carbon fiber pins [30], three-dimensional conductive paths formed by z-pins in the laminates provide the possibility for damage detection [31,32]. For z-pinned composites, the existence of carbon fiber z-pins enhances the sensitivity of *in situ* damage monitoring within the laminates [33,34].

In this article, we aimed to analyze the effect of different pin properties on the interlaminar fracture toughness of z-pinned composites. The failure behaviors of z-pin debonding and pulling out were observed via the z-pin traction load test and the failure morphologies. Meanwhile, the electrical resistance of laminates was measured in real time to reflect steady or stick-slip crack growth of the control sample and the z-pinned composites, respectively. The sensitivity of different pins to damage monitoring was evaluated. The crack length–displacement curve was created by the established equation and accurately corresponded to the load–displacement curve of the double cantilever test.

2 Experimental

2.1 Materials

Carbon fiber unidirectional prepreg UIN10000/9A16 was purchased from China Weihai Guangwei Composite Material Co., Ltd. This unidirectional prepreg consisted of CCF800 carbon fiber and 9A16 epoxy resin, and its resin content was 33–34%. The area density of prepreg was

100 g/m², and the thickness of cured single ply was about 0.1 mm. CCF300 and CCF800 carbon fibers were used to prepare the pins that had a diameter of 0.5 mm. The length of the z-pins was 4 mm.

2.2 Fabrication of z-pinned carbon fiber/epoxy composites

The ply scheme of the composite laminates for DCB tests was set as $[0]_{40}$, and a PTFE film with a thickness of 13 μm was placed in the midplane of the laminates during lay-up to form an initiation site for the delamination. CCF300 or CCF800 z-pins were implanted in the crack propagation region. The prepregs were heated to soften on a hot table at $30 \pm 1^\circ\text{C}$. The carbon fiber pins were embedded vertically into the prepregs. The rest of the pins were cut off from the top surface of the prepregs. The crack propagation region of the specimen covering an area of $25\text{ mm} \times 65\text{ mm}$ was inserted with 48 z-pins arranged in a square grid pattern consisting of four columns (0° direction) and twelve rows (90° direction). The volume fraction of z-pins was 0.6 vol% with a pin-to-pin spacing of 5 mm. The z-pinned composite samples were cured in an autoclave at a pressure of 0.5 MPa. The temperature scheme was $80^\circ\text{C}/30\text{ min} + 120^\circ\text{C}/90\text{ min}$, and the heating rate was controlled at $1^\circ\text{C}/\text{min}$.

2.3 Characterization and testing

2.3.1 Double cantilever beam test

Mode I interlaminar fracture toughnesses (G_{IC}) of control and z-pinned composites were measured using the DCB test in accordance with ASTM D5528. The specimen size was $160\text{ mm} \times 25\text{ mm}$. As shown in Figure 1a and b, aluminum loading blocks were bonded to top and bottom surfaces at the sample edge. The size of the loading blocks was $30\text{ mm} \times 25\text{ mm} \times 8\text{ mm}$. The loading block connects with a hinge via a bolt. Thus, the load was maintained perpendicular to the sample during the test. The initial crack length, set to 50 mm, was measured from the midpoint of the loading block to the end of the inserted PTFE film. Before the DCB test, both the edges of the specimen were coated just ahead of the insert with a thin layer of white background. The 60 mm from the insert film on either edge was marked with thin vertical lines every 1 mm. During the DCB test, a traveling optical

Figure 1: Schematic illustration of the experimental specimens for the (a) DCB test and (c) z-pin traction load test; the photograph of the (b) DCB test and (d) the z-pin traction load test.

microscope was used to record the crack growth at every 1 mm, up to a mark of 60 mm. The delamination length of the sample was the sum of the initial crack length and the increment of the growth determined from the tick marks. The DCB test was carried out at a crosshead speed of 1 mm/min by using Instron 3344 universal testing machine with a 5 kN loading cell. Five samples of each type of composite were tested under identical conditions. The G_{IC} values were calculated based on the corrected modified beam theory (MBT) formula as follows:

$$G_{IC} = \frac{3P_C\delta}{2b(a + |\Delta|)} \times F, \quad (1)$$

where δ is the load point displacement, P_C is the applied load, a is the crack length, b is the specimen width, and Δ is the effective delamination extension to correct for the rotation of DCB arms at the delamination front, and F is the large displacement effects correction parameter given by

$$F = 1 - \frac{3}{10} \left(\frac{\delta}{a} \right)^2 - \frac{3}{2} \left(\frac{\delta t}{a^2} \right), \quad (2)$$

where t is the sum of the one-half thickness of the loading block and one-fourth thickness of the DCB sample.

2.3.2 Z-pin traction load test

To analyze the failure behavior of z-pin during the crack opening, the tensile test along the thickness direction of the composite laminate was carried out to measure the z-pin traction load. The specimen consisted of two parts of carbon fiber/epoxy laminate that were separated by the PTFE film in the middle plane. The specimen had a dimension of 30 mm × 25 mm, which contained the z-pin array in an implantation area of 1 cm², as shown in Figure 1c and d. The volume fraction of z-pin was controlled at 0.4, 1.2, and 2.4 vol%, which corresponded to the z-pin number of 2, 6, and 12, respectively. The

specimens were tested at a tensile speed of 1 mm/min by using Instron 3344 machine with a 5 kN loading cell. Five samples of each type of composite were tested under identical conditions.

2.3.3 Z-pin tensile test

To further analyze the influence of carbon fiber pin properties on the G_{IC} of the laminates, the tensile property of z-pin was measured by using Instron 3382 universal testing machine at a tensile speed of 1 mm/min in accordance with ASTM D4018. Both the ends of impregnated fiber tow were bonded on a stiffener tab with a gauge length of 250 mm. Five samples of each type of composite were tested under identical conditions.

2.3.4 Electrical resistance measurement

DMM6500 digital multimeter was used to measure the electrical resistance of the composite laminate. Copper foil electrodes were bonded to the sample edges by using silver glue, which ensured a good electrical connection between the specimen and the electrodes. The *in situ* measurement setup of the electrical resistance during the DCB test is shown in Figure 2.

2.3.5 Morphology observation

A three-dimensional optical microscope system VHX-6000 was used to examine z-pin morphologies and the fracture surface of the measured specimen. Images

were taken at different magnifications in order to investigate the factors of interlaminar fracture toughness improvement.

3 Results and discussion

3.1 Mode I interlaminar fracture toughness of z-pinned composites

The representative load–displacement curves of control and z-pinned composites during DCB tests are shown in Figure 3a. These load–displacement curves can be divided into linear and nonlinear regions. The linear region indicates no fiber bridging effect before crack initiation due to the presence of the PTFE film. The initiation value for G_{IC} should be recorded corresponding to the load and displacement when the crack contacts the first vertical mark after the precrack tip. The control and z-pinned samples show different load–displacement curve profiles in the nonlinear regions. For the control sample, the load values drop smoothly. The crack propagates at a constant velocity in the midplane of the laminate, while the load–displacement curves of the two z-pinned composites show a jagged profile. This phenomenon manifests that z-pins play an important role in the way of crack growth. The way of crack growth is changed from the stable propagation in the control sample to “stick–slip” behavior in z-pinned samples. When the crack contacts a row of z-pins, the load values increase steadily. As the opening displacement increases, z-pins bridge the delamination at the crack tip, and then the z-pins are debonded and pulled out from the surrounding laminates. Once they are pulled out completely, the accumulated energy is partially released and the crack propagates suddenly. The load values display a sharp reduction. The load values increase again when the crack tip contacts the next row of the z-pins. Therefore, the load values show the periodical drop and increase during the crack propagation.

Figure 3b shows the delamination resistance curve of the control sample and the z-pinned composites. The G_{IC} of the control sample is increased gradually and tends to be stable when the crack length reaches 70 mm. The interlaminar fracture toughness of the control sample is dominated by fiber bridging. As the crack propagates, the bridging fibers are broken or pulled out from the resin due to the separation of the double cantilever beam. When the number of bridging fibers per unit crack area is equal, the steady fracture toughness will be obtained. The fracture toughness values of the z-pinned composites

Figure 2: *In situ* monitoring of electrical resistance during the DCB test.

Figure 3: (a) Typical mode I load–displacement curves of DCB tests, (b) delamination resistance curve, and (c) mode I initiation and propagation fracture toughness values of control and z-pinned composites.

are much higher than that of the control sample. The pinning effect of the z-pins suppresses the extension of the crack tip. The failure behaviors of the z-pins debonding and pulling out absorb energy to enhance the delamination resistance of the laminates.

Figure 3c shows the initiation and propagation G_{IC} values of the control and z-pinned composites. The initiation G_{IC} value of the control sample is 201.2 J/m², while the initiation G_{IC} values of CCF300 and CCF800 z-pinned composites are 518.5 and 564.6 J/m², respectively. The propagation G_{IC} value of the control sample is 397.6 J/m², and the propagation G_{IC} values of CCF300 and CCF800 z-pinned composites are 1980.8 and 1902.1 J/m², respectively. These results demonstrate that z-pins provide the crack bridging traction load, resulting in the significant enhancement of interlaminar fracture toughness. The tensile

properties of z-pins are listed in Table 1. The tensile modulus of the CCF800 carbon fiber is higher than that of the CCF300 carbon fiber. The CCF300 pins are prone to bending when the delamination surfaces separate from each other. The bending deformation could absorb partial energy, resulting in the slightly higher propagation G_{IC} value of the CCF300 z-pinned composite than that of the CCF800 z-pinned composite.

3.2 Fracture surface morphologies and failure mechanism

Figure 4a shows the opening crack morphology of the z-pinned specimen during the DCB test. As the crack length reaches 110 mm, the crack opening displacement (COD) of the control sample is 18 mm, while the COD of the z-pinned composite is increased significantly to 35 mm. In the z-pinned composites, z-pins provide the traction load during the delamination process, which effectively suppresses the crack tip extension. Therefore, the z-pinned composites need larger crack opening displacement to induce crack to propagate to the same length as the control sample.

Table 1: Tensile properties of the different z-pin fibers

	Strength (MPa)	Modulus (GPa)	Strain (%)
CCF300	4419 ± 165	232 ± 4	1.98 ± 0.12
CCF800	5607 ± 133	292 ± 7	1.93 ± 0.07

Figure 4: (a) Photographs of crack opening during the DCB test, and failure morphologies of (b) CCF300 and (c) CCF800 specimens.

Figure 4b and c show the failure morphologies of CCF300 and CCF800 z-pinned specimens, respectively. The cracks in these two z-pinned composites also propagate in the middle layer during the DCB test. The bridging carbon fibers and pulling out z-pins in the midplane reduce the stress concentration in the crack front.

Figure 5a and b show the surface morphologies of CCF300 and CCF800 z-pins in the fractured samples. The polymer resin partially wraps z-pins as seen in the white area. When z-pin is inserted into the unidirectional laminate, an eye-shaped resin-rich region is formed around the z-pins. During the z-pins pulling out from the eye-shaped region, microcracks form at the z-pin/laminate interface or inside the resin. A part of white resin attached to the z-pin is pulled out together. The wrapped resin on the z-pin surface indicates the presence of the interfacial force between the z-pins and the laminate.

To further analyze the interface adhesion strength between the z-pin and laminate, the traction loads at different z-pin volume fractions were measured via the z-pin traction load test [35], as shown in Figure 6a. A maximum load of 2.4 vol% sample is increased to 581 N from 109 N of 0.4 vol% sample. All these load–displacement curves at different z-pin volume fractions can be divided into three stages: (1) z-pins initially exert elastic traction load to resist delamination crack opening; (2) when the bridge traction load reaches the peak point,

Figure 5: Morphologies and profiles of (a) CCF300 and (b) CCF800 z-pins in the fractured samples.

Figure 6: (a) Representative load–displacement curves at different z-pin volume fractions during z-pin traction load test; (b) the relationship between the traction load with the number of z-pins.

z-pins are debonded from the surrounding laminate through the interface shear cracking, and consequently, the load values are dropped partially. The shear cracking occurs once the traction load exceeds the shear failure stress of the z-pin/laminate interface; (3) during z-pins pulling out from the laminate, the bridging traction load is decreased with the increase of the crack opening displacement. In the third stage, the sliding action of the z-pin generates the friction traction load that contributes to the improvement of the G_{IC} values. Finally, z-pins are pulled out of the composite laminate completely and the traction load is decreased to zero. In order to obtain the interfacial shear failure load between the single z-pin and laminate, the traction load was normalized. The interfacial shear failure load of a single z-pin is 46.5 N, as shown in Figure 6b.

Figure 7 displays the failure morphologies at different z-pin volume fractions during the z-pin traction load test.

z-pin pull-out failure mode is observed for all these samples. This indicates that the failure mode of z-pins is not affected by the z-pin volume fraction in the z-pin traction load test.

3.3 *In situ* damage sensing

In situ damage monitoring of control and z-pinned composites was demonstrated by measuring the real-time electrical resistance during the DCB test. The electrical response in the DCB test is distinct from that under the tensile or flexural test [36,37]. The geometric parameters of the DCB specimen and the *in situ* monitoring method are shown in Figure 8. The electrodes were electrically connected to the top and bottom surfaces of the DCB specimen. These two electrodes were designed to measure

Figure 7: Side and top views of failure morphologies at z-pin volume fractions of (a) 0.4 vol%, (b) 1.2 vol%, and (c) 2.4 vol% during z-pin traction load test.

Figure 8: Schematic diagram of the measurement method for the electrical resistance at (a) initial state and (b) crack propagation state during the DCB test.

the through-thickness electrical resistance of the DCB specimen [38], as shown in Figure 8a. Accompanied by crack propagation, the conduction area of the double cantilever beam is decreased. Thus, the electrical resistance increases gradually, as shown in Figure 8b. Therefore, the crack growth process of laminates was reflected via the electrical resistance change during the DCB test.

The load–displacement curves of control, CCF300, and CCF800 z-pinned composites along with the corresponding electrical resistance curves are shown in Figure 9. With the increase of the crack opening displacement,

the load values are decreased gradually for the control sample. The corresponding electrical resistance change, $\Delta R/R_0$, is increased linearly, which reflects that the crack propagates at a uniform speed in the midplane of the control sample. For CCF300 and CCF800 z-pinned composites, the $\Delta R/R_0$ is increased in a stepwise fashion. This phenomenon reflects that the periodical extension and arrest of cracks occur in the z-pinned composites, as shown in Figure 10b and c. The different $\Delta R/R_0$ curve profiles clearly manifest two ways of crack propagation during the DCB test.

Figure 9: The load–displacement curve (blue) and electrical resistance change curve (red) of (a) control, (b) CCF300, and (c) CCF800 z-pinned composites.

Figure 10: The calculated crack length with respect to the opening displacement for (a) control, (b) CCF300, and (c) CCF800 z-pinned composites.

The $\Delta R/R_0$ curves of CCF300 and CCF800 z-pinned composites demonstrate that the step heights in the $\Delta R/R_0$ curve are increased step by step with the increase of the displacement. According to Ohm's law, $R = \rho L/S$, where R is the resistance, ρ is the resistivity, L is the length, and S is the cross-sectional area. There is a non-linear relationship between the conduction area and the electrical resistance. In order to accurately monitor the crack growth in the DCB sample, the relationship between the resistance change and the crack growth length was calculated by Ohm's law. The electrical resistances of the DCB specimen in the initial state and crack propagation state are shown in equations (3) and (4):

$$R_0 = \frac{\rho t}{cw} + R_x, \quad (3)$$

$$R = \frac{\rho t}{(c - \Delta a)w} + R_x, \quad (4)$$

where t is the specimen thickness, w is the specimen width, c is the length from the precrack front to the other end side of DCB specimen, R is the through-thickness electrical resistance at a crack length of $a_0 + \Delta a$, R_0 is the initial electrical resistance before crack propagation, and R_x is the electrical resistance of the other parts of the

circuit including the electrical resistance along the fiber direction of the initial crack region and the contact resistance between the electrodes and the composite laminates. To eliminate R_x , formula (5) is obtained by subtracting equation (3) from equation (4):

$$R - R_0 = \Delta R = \frac{\rho t}{(c - \Delta a)w} - \frac{\rho t}{cw}. \quad (5)$$

Equation (5) may be rewritten as equation (6):

$$\Delta a = \left(1 - \frac{\rho t}{\Delta R cw + \rho t}\right)c. \quad (6)$$

The relationship between ΔR and Δa is established in equation (6). The crack lengths at different displacements are determined according to the ΔR value. Thus, an *in situ* monitoring method for crack length was developed based on the electrical resistance change. Figure 10 shows the crack length and displacement curve for control, CCF300, and CCF800 z-pinned composites. As seen in Figure 10, the crack length is constant in the linear region of the load–displacement curve. For the control sample, the crack growth rate is decreased with the increase of the crack opening displacement in the nonlinear region of load–displacement curve. The cracks in CCF300 and

Figure 11: The relationship between $\Delta R/R_0$ and the crack length for control, CCF300, and CCF800 z-pinned composite.

CCF800 z-pinned composites show obvious crack propagation and retention processes. These crack growth processes correspond with the jagged load–displacement curve. The load is increased when the crack length slightly increases, and then the load is dropped sharply as the crack propagates rapidly. The amplitude of sharp load reductions is positively correlated with the rapid crack propagation lengths. The crack growth status is accurately correlated with the load–displacement curve by monitoring the resistance change, which provides a convenient method to calculate G_{IC} and analyze the crack growth process of the DCB specimen.

Figure 11 shows the relationship between $\Delta R/R_0$ and the crack length during the DCB test for control and z-pinned composites. The $\Delta R/R_0$ values increase with the increase of crack length for all three samples, and the increasing rate of $\Delta R/R_0$ value with crack length becomes bigger. When the crack propagates to 110 mm, $\Delta R/R_0$ values of CCF300 and CCF800 z-pinned composites are increased to 9.1 and 14.3%, which is much higher than the $\Delta R/R_0$ value of 5.9% for the control sample. These results demonstrate that z-pins greatly enhance the interlaminar performance and improve the sensitivity of damage detection.

4 Conclusion

This article successfully fabricated z-pinned carbon fiber/epoxy composites by using CCF300 and CCF800 carbon fiber pins. The values of the mode I interlaminar fracture toughness of the CCF300 and CCF800 z-pinned composites

are increased to 1,981 and 1,902 J/m² from 397 J/m² for the control sample. The debonding and pull-out of the z-pins dominate the improvement of the interlaminar fracture toughness. A strong interface is formed between the z-pin and the surrounding laminate. The interfacial shear failure load of a single z-pin is 46.5 N. Moreover, the method of *in situ* damage monitoring via electrical resistance measurement was established. The two different crack growth ways, stable crack growth in the control sample and stick-slip crack propagation in z-pinned composites, are clearly reflected by the electrical resistance curve. Z-pins enhance the sensitivity of delamination detection. The $\Delta R/R_0$ values of CCF300 and CCF800 z-pinned composites are increased to 9.1 and 14.3% from 5.9% of the control sample. The quantitative relationship between the crack length and the electrical resistance change of the DCB specimen was also established. The direct reflection of the crack growth process develops a convenient way for the delamination failure analysis of composites.

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References

- [1] Hamer S, Leibovich H, Intrater R, Zussman E, Sherman D. Mode I interlaminar fracture toughness of Nylon 66 nanofibrillat interleaved carbon/epoxy laminates. *Polym Compos.* 2011;32(11):1781–9.
- [2] Arai M, Hirokawa JI, Hanamura Y, Ito H, Hojo M, Quaresimin M. Characteristic of mode I fatigue crack propagation of CFRP laminates toughened with CNF interlayer. *Compos Part B.* 2014;65:26–33.

- [3] Wang J, Ma C, Chen G, Dai P. Interlaminar fracture toughness and conductivity of carbon fiber/epoxy resin composite laminate modified by carbon black-loaded polypropylene non-woven fabric interleaves. *Compos Struct.* 2020;234:111649.
- [4] An WJ, Kim CH, Choi JH, Kweon JH. Static strength of RTM composite joint with I-fiber stitching process. *Compos Struct.* 2019;210:348–53.
- [5] Ahmed S, Zheng X, Zhang D, Yan L. Impact response of carbon/kevlar hybrid 3D woven composite under high velocity impact: experimental and numerical study. *Appl Compos Mater.* 2020;27(3):1–21.
- [6] Bilisik K, Sapanc E, Karaduman NS. Flexural characterization of 3D prepreg/stitched carbon/epoxy/multiwall carbon nanotube preforms and composites. *J Compos Mater.* 2018;53:5.
- [7] Grassi M, Zhang X, Meo M. Prediction of stiffness and stresses in z-fibre reinforced composite laminates. *Compos Part A Appl Sci Manuf.* 2002;33(12):1653–64.
- [8] Mouritz AP, Chang P. Tension fatigue of fibre-dominated and matrix-dominated laminates reinforced with z-pins. *Int J Fatigue.* 2010;32(4):650–8.
- [9] Mouritz AP. Compression properties of z-pinned composite laminates. *Compos Sci Technol.* 2007;67(15–16):3110–20.
- [10] Chang P, Mouritz AP, Cox BN. Flexural properties of z-pinned laminates. *Compos Part A Appl Sci Manuf.* 2007;38(2):244–51.
- [11] Chang P, Mouritz AP, Cox BN. Properties and failure mechanisms of z-pinned laminates in monotonic and cyclic tension. *Compos Part A Appl Sci Manuf.* 2006;37(10):1501–13.
- [12] Mouritz AP, Chang P, Isa MD. z-pin composites: aerospace structural design considerations. *J Aerosp Eng.* 2011;24(4):425–32.
- [13] Mouritz AP. Review of z-pinned laminates and sandwich composites. *Compos Part A Appl Sci Manuf.* 2020;139:106128.
- [14] Mouritz AP. Review of z-pinned composite laminates. *Compos Part A Appl Sci Manuf.* 2007;38(12):2383–97.
- [15] Dai S-C, Yan W, Liu H-Y, Mai Y-W. Experimental study on z-pin bridging law by pullout test. *Compos Sci Technol.* 2004;64(16):2451–7.
- [16] Li C, Wu Z, Meng Z, Li M. Influential factors of z-pin bridging force. *Appl Compos Mater.* 2014;21(4):615–31.
- [17] Knaupp M, Scharr G. Manufacturing process and performance of dry carbon fabrics reinforced with rectangular and circular z-pins. *J Compos Mater.* 2013;48(17):2163–72.
- [18] Cartié D, Partridge IK. Delamination behaviour of z-pinned laminates. *Eur Struct Integr Soc.* 1999;27:27–36.
- [19] Cartié DDR, Troulis M, Partridge IK. Delamination of z-pinned carbon fibre reinforced laminates. *Compos Sci Technol.* 2006;66(6):855–61.
- [20] Partridge IK, Cartié DDR. Delamination resistant laminates by z-fiber® pinning: Part I manufacture and fracture performance. *Compos Part A Appl Sci Manuf.* 2005;36(1):55–64.
- [21] Kravchenko SG, Kravchenko OG, Carlsson LA, Pipes RB. Influence of through-thickness reinforcement aspect ratio on mode I delamination fracture resistance. *Compos Struct.* 2015;125:13–22.
- [22] Ladani RB, Ravindran AR, Wu S, Pingkarawat K, Kinloch AJ, Mouritz AP, et al. Multi-scale toughening of fibre composites using carbon nanofibres and z-pins. *Compos Sci Technol.* 2016;131:98–109.
- [23] Virakthi A, Kwon S, Lee S, Robeson M. Delamination resistance of composite laminated structures reinforced with angled, threaded, and anchored z-pins. *J Compos Mater.* 2018;53:1507–19.
- [24] M'Membe B, Yasaei M, Hallett S, Partridge I. Effective use of metallic z-pins for composites' through-thickness reinforcement. *Compos Sci Technol.* 2019;175:77–84.
- [25] Pingkarawat K, Mouritz AP. Comparative study of metal and composite z-pins for delamination fracture and fatigue strengthening of composites. *Eng Fract Mech.* 2016;154:180–90.
- [26] Zhang Y, Wang S, Zhao X, Wang F, Wu G. In situ study on fracture behavior of z-pinned carbon fiber-reinforced aluminum matrix composite via scanning electron microscope (SEM). *Materials.* 2019;12(12):1941.
- [27] Bolotin VV. Delaminations in composite structures: Its origin, buckling, growth and stability. *Compos Part B Eng.* 1996;27(2):129–45.
- [28] Gros XE, Ogi K, Takahashi K. Eddy Current, Ultrasonic c-scan and scanning acoustic microscopy testing of delaminated quasi-isotropic CFRP materials: a case study. *J Reinf Plast Compos.* 1998;17:389–405.
- [29] Xu D, Liu PF, Chen ZP, Li JG, Wang LL. Delamination analysis of carbon fiber/epoxy composite laminates under different loading rates using acoustic emission. *J Fail Anal Prev.* 2019;19(11):1034–42.
- [30] Pegorin F, Pingkarawat K, Mouritz AP. Electrical-based delamination crack monitoring in composites using z-pins. *Compos Part A Appl Sci Manuf.* 2018;104:120–8.
- [31] Zhang H, Liu Y, Kuwata M, Bilotti E, Peijs T. Improved fracture toughness and integrated damage sensing capability by spray coated CNTs on carbon fibre prepreg. *Compos Part A Appl Sci Manuf.* 2015;70:102–10.
- [32] Shen L, Liu L, Wang W, Zhou Y. In situ self-sensing of delamination initiation and growth in multi-directional laminates using carbon nanotube interleaves. *Compos Sci Technol.* 2018;167:141–7.
- [33] Zhang B, Allegri G, Hallett SR. An experimental investigation into multi-functional z-pinned composite laminates. *Mater Des.* 2016;108:679–88.
- [34] Zhang B, Allegri G, Yasaei M, Hallett SR, Partridge IK. On the delamination self-sensing function of z-pinned composite laminates. *Compos Sci Technol.* 2016;128:138–46.
- [35] Mouritz AP, Koh TM. Re-evaluation of mode I bridging traction modelling for z-pinned laminates based on experimental analysis. *Compos Part B Eng.* 2014;56(Jan):797–807.
- [36] Rausch J, Maeder E. Health monitoring in continuous glass fibre reinforced thermoplastics: Tailored sensitivity and cyclic loading of CNT-based interphase sensors. *Compos Sci Technol.* 2010;70(13):2023–30.
- [37] Gao L, Thostenson ET, Zhang Z, Chou TW. Sensing of damage mechanisms in fiber-reinforced composites under cyclic loading using carbon nanotubes. *Adv Funct Mater.* 2009;19(1):123–30.
- [38] Du X, Zhou H, Sun W, Liu H-Y, Zhou G, Zhou H, et al. Graphene/epoxy interleaves for delamination toughening and monitoring of crack damage in carbon fibre/epoxy composite laminates. *Compos Sci Technol.* 2017;140:123–33.