Available online at www.sciencedirect.com
ScienceDirect
Composites Science and Technology 67 (2007) 1294–1301
COMPOSITES SCIENCE AND TECHNOLOGY
www.elsevier.com/locate/compscitech

Experimental study on effect of loading rate on mode I delamination of z-pin reinforced laminates

Hong-Yuan Liu [a,*], Wenyi Yan [b], Xiao-Yan Yu [a], Yiu-Wing Mai [a]

[a] Centre for Advanced Materials Technology, School of Aerospace, Mechanical and Mechatronic Engineering J07, University of Sydney, Sydney, NSW 2006, Australia
[b] School of Engineering and Information Technology, Deakin University, Geelong, Vic. 3217, Australia

Received 7 April 2006; received in revised form 28 August 2006; accepted 3 October 2006
Available online 17 November 2006

Abstract

This paper presents an experimental investigation on mode I delamination of z-pinned double-cantilever-beams (DCB) and associate z-pin bridging mechanisms. Tests were performed with three types of samples: big-pin with an areal density of 2%, small-pin with an areal density of 2% and small-pin with an areal density of 0.5%. The loading rates for each type of samples were set at 1 mm/min and 100 mm/min. Comparison of fracture load under different loading rates shows the rate effects on delamination crack opening and delamination growth. Optical micrographs of z-pins after pullout were also presented to identify the bridging mechanisms of z-pins under different loading rates.

Keywords: A. Z-Pin reinforcement; C. Z-Pin bridging law; D. DCB mode I delamination; D. Loading rate

1. Introduction

Z-Pin, also called *Z-Fiber*™, [1] is a novel technique which was developed to increase the strength of laminated composites in the thickness direction, that is, z-direction. Its capacity to ensure significant increase in the delamination resistance of laminated composites has been verified by both industrial applications and laboratory tests. Cartie and Partridge [2–4] have presented the first research results on mode I and mode II delamination toughness of z-pinned laminates and developed the basic knowledge on the subject. Subsequently, there were many experimental and numerical evaluations on the delamination resistance provided by z-pinning under typical mode I, mode II and mixed mode I/II loadings carried out in the last five years [5–11]. With rapid expansion of the application of composites, composite structures often face rather complex in-service conditions, one of which is the effect of loading rate. Dynamic delamination without z-pin reinforcement has already been studied for more than 30 years [12,13]. Recently, Sridhar et al. [14] presented a theoretical study on delamination dynamics in through-thickness reinforced laminates. The simulation results from their model showed that at a high crack velocity, the kinetic energy term dominates the overall energies and the effect of the through-thickness reinforcement on the delamination growth is not as significant as that for low velocity or quasi-static crack growth. Also in their study, only a high rate delamination was considered but the effect of loading rate on the z-pin bridging mechanisms was not examined.

Fig. 1 shows a double-cantilever-beam (DCB) specimen with z-pin reinforcement. During mode I delamination, a reinforcing z-pin provides a closure stress to the opening crack. The functional relationship between closure stress and delamination crack-opening from a single pin is called the “bridging law”, which can be evaluated in principle by a z-pin pullout test [15]. The efficiency of z-pin reinforcement is strongly dependent on the bridging mechanisms [6]. When the loading rate is high, a high-rate shear/friction

---

[*] Corresponding author. Tel.: +61 2 93517148; fax: 61 2 93513760.
E-mail address: liu_hy@aeromech.usyd.edu.au (H.-Y. Liu).

0266-3538/$ - see front matter © 2006 Elsevier Ltd. All rights reserved.
doi:10.1016/j.compscitech.2006.10.001

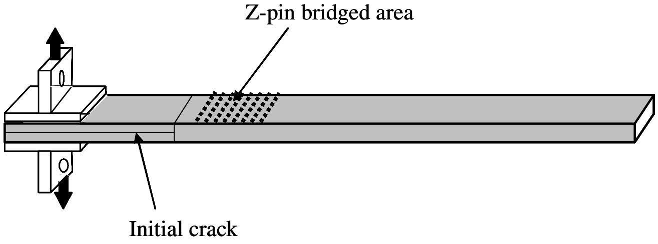

Fig. 1. DCB specimen with z-pinning reinforcement.

between the pin and the laminates may cause a significant change in the z-pin pullout behaviour which changes the z-pin bridging mechanism accordingly. However, to-date, no rigorous theoretical models or experimental results have been provided to investigate the effect of loading rate on the z-pin bridging mechanisms. Furthermore, in a DCB mode I delamination, during the delamination crack opening, the embedded z-pins can also provide resistant moments to the bent beams when the z-pin's stiffness is high. At a high loading rate, the cross-head displacement of the beam is increased at a very high rate. However, the delamination crack may not propagate at the same rate due to the resistance imposed by the z-pins. At a certain crack length and a certain applied displacement, the curvature of the beam under a high loading rate would be different from that under a low loading rate. It means that z-pins under different loading rates may suffer different bending before being pullout. Consequently, their resistances to the bent beam are different. This effect has not been considered in previous studies.

This paper presents an experimental study on the effects of loading rate on the fracture load of z-pinned DCB mode I delamination. Loading rates of 1 and 100 mm/min, respectively, were chosen and corresponding load–displacement curves were obtained. Optical micrographs of z-pin microstructure after pullout were provided to examine the z-pin damage under different loading rates. Results of cross-head displacement *versus* crack length were also presented to reveal the bending resistance of the DCB. Tests were carried out for three types of samples: small-pin reinforcement with areal densities of 0.5% and 2%, and big-pin reinforcement with an areal density of 2%, in which the areal density is defined as the ratio of the total cross-section area of the pins to the z-pin bridged area. These results show that the loading rate has a noticeable effect not only on the pullout/fracture load but also on the failure mechanisms. Experimental results of z-pin pullout under the same loading rates were also provided to gain a better understanding of the results obtained from the DCB tests.

2. Experimental procedure and results

2.1. Z-pinned DCB tests

The experimental configuration for z-pinned DCB mode I test is shown in Fig. 1. The laminated beams were made of carbon fibre (IMS) reinforced epoxy (9 2 4) (unidirectional) with dimensions: 150 mm in length, 20 mm in width and 1.5 mm in thickness. The pultruded T300/bismaleimide pins were vertically inserted into the beams by an ultrasonic insertion machine before curing [2]. A thermal insulated film with a length of 50 mm was inserted between the upper and lower beams to create an initial crack between them. Two T-shaped tabs were glued to the top and bottom surfaces of the laminates and were firmly gripped for testing in an Instron 5567 universal machine at cross-head speeds (V) of 1 and 100 mm/min, respectively. Load–displacement traces were recorded until the delamination crack propagated to the right end of the beams. Crack growth was recorded by a video camera with a microscope. In all samples, the first column of z-pins was located at 5 mm away from the initial delamination tip and the length of pinned region was 25 mm. Three types of samples were tested, which were (1) big-pin reinforced DCB with an areal density $D = 2\%$; (2) small-pin reinforced DCB with an areal density $D = 2\%$ and (3) small-pin reinforced DCB with an areal density $D = 0.5\%$. Three samples were tested in each case. The results given in the following sections were only average values. In Figs. 3, 7 and 11, the maximum and minimum values were also given to show the variations in the fracture load. These variations can be caused by several reasons. During crack growth, the fracture load increased when the crack reached the pins. Changes in the pin/composite interface may cause similar changes in the peak load. Between any two columns of pins, the crack grew unstably. When the crack spread through most length of the pinned region, in some small-pin reinforced samples, the crack passed two columns of pins without any increase in the fracture load. In this case, it was very hard to measure the crack length accurately. Furthermore, the z-pins were supposed to be inserted in the thickness direction of the laminates. However, a problem often encountered with z-pinning is that the pins become misaligned from the vertical direction during insertion. The maximum misalignment angle of both small and big pins may be larger than 10° [16]. The misalignment of the z-pins in the specimens certainly caused deviations in the bridging forces of z-pins. Consequently, it caused deviations in the fracture loads.

2.2. Z-pin pullout test

The test set-up for pullout of a 3×3 z-pin sample is shown in Fig. 2. The z-pins and pre-pregs were made of the same materials as were used for the DCB samples. The prepreg was 40 mm long and 20 mm wide. A thermal insulated film with a thickness of 10 μm was inserted between the upper and lower laminates to avoid any adhesive bonding between them. The thickness of the sample was 3 mm. Two T-shaped tabs were glued to the top and bottom surfaces of the laminates and were firmly secured in an Instron 5567 testing machine at cross-head speeds of 1 mm/min and 100 mm/min, respectively. Load–displacement curves were

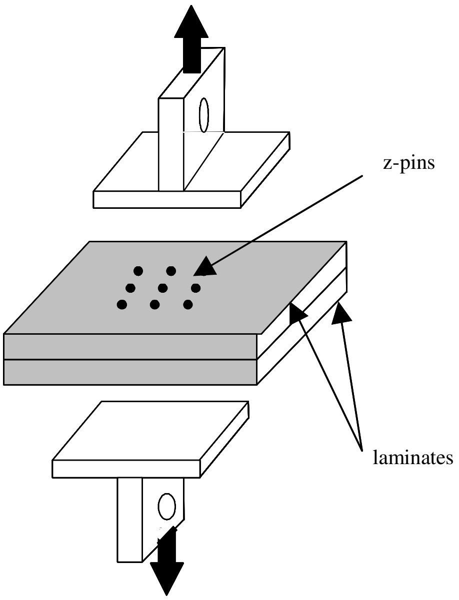

Fig. 2. Illustration of experimental configuration for 3 × 3 z-pins pullout tests.

recorded until the pins were completely pulled out. Three samples were tested in each case. The results were given by the average values. The bars in Figs. 4b and 8b show the maximum and minimum values of the pullout stress. More details of the pullout tests were given in [15].

2.3. Results of DCB mode I delamination and z-pin pullout tests

2.3.1. Results of DCB samples with high density big-pin reinforcement

Fig. 3 shows the load-crack length curves of big-pin reinforced DCB delamination, in which the z-pin diameter, d, is 0.51 mm and the areal density, D, is 2% (8 columns × 6 rows). It is shown that at the higher loading rate, a larger applied load was needed to propagate the delamination crack. To understand the effect of loading rate on the delamination resistance, z-pin pullouts on both big-pin and small-pin samples were conducted. Fig. 4a shows an experimental bridging load-displacement curve of a typical big-pin pullout test [15]. It is shown that with increasing displacement, the bridging force increased until it reached a maximum value, $P_{\max}$. At this value, the pins were debonded from the laminates and then pulled out from the laminates with increasing displacement. At this stage, the bridging force was caused by the interfacial friction between the z-pins and the laminates. The results of the maximum frictional bridging stresses calculated from the bridging forces for different pullout rates are given in Fig. 4b, in which, $\sigma_{\max}$ is the average stress given by a single pin. Clearly, at the higher rate, the bridging stress is higher. Since the bridging stress is the most dominant parameter in z-pin bridging, this explains satisfactorily why the fracture load increases with loading rate as shown in Fig. 3.

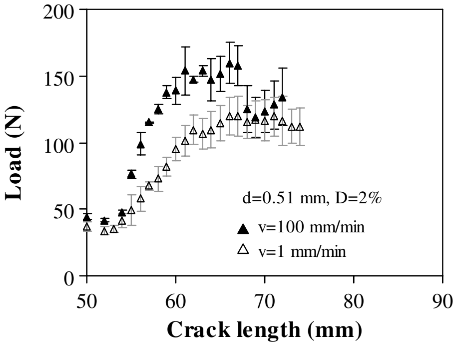

Fig. 3. Load-crack length curve of z-pinned DCB mode I delamination test, in which $d = 0.51$ mm, $D = 2\%$, $v = 1$ mm/min and 100 mm/min, respectively.

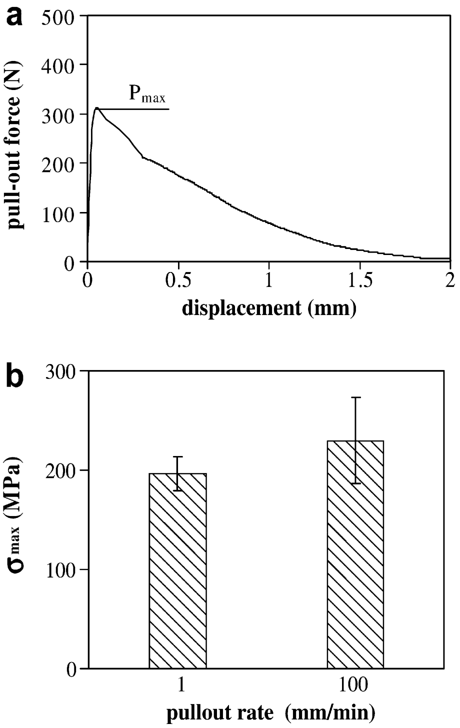

Fig. 4. (a) An experimental load–displacement curve of 3 × 3 big-pin pullout; (b) maximum bridging stress of z-pin pullout test, in which, $d = 0.51$ mm, $v = 1$ mm/min and 100 mm/min, respectively.

Furthermore, besides the bridging force, the resistant bending moment from the z-pins can also provide resistance to delamination growth, especially when the stiffness and the density of the pins are high enough. At the higher loading rate, the cross-head displacement of the beam was increased very fast, which was 100 times higher than that at the lower loading rate. However, the delamination crack could not always propagate at the same rate due to the resistance imposed by the z-pins. Fig. 5 shows the relationship between the cross-head displacement of the DCB and the delamination crack length. It is found that at a certain crack length, the radius of curvature of

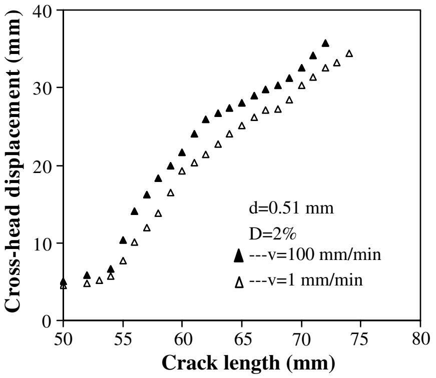

Fig. 5. Cross-head displacement of DCB versus delamination crack length of big-pin samples, in which, $D = 2\%$, $v = 1$ mm/min and 100 mm/min, respectively.

the beams under the higher loading rate was smaller than that under the lower loading rate. It means that z-pins under a high loading rate suffered more severe bending during pullout. As a reaction, the reinforcing pins provided a higher resistance to the bent beam to delay the delamination. A higher applied load was hence required for further crack growth. In addition, when the pins were bent, its embedded length applied an additional pressure to the laminates as a reaction to the bending. This pressure increased the "snubbing" friction against pin pullout which, consequently, caused an increase in the fracture resistance.

Fig. 6a and b shows the optical photomicrographs of z-pins that were pulled out after the DCB tests. The images of typical z-pin ends after the DCB tests are shown in Fig. 6c and d. An interesting fact is that when the loading rate was low, the z-pin was pulled out without any obvious damage. However, when the loading rate was high, the z-pin was pulled out accompanied by a number of splits along the length of the pin, which could be seen as evidence of considerable shearing during bending of the beams. It should be noted that these observed results are highly repeatable.

2.4. Results of DCB samples with high density small-pin reinforcement

The results of the small-pin reinforced DCB tests are shown in Fig. 7, where the laminated beams were reinforced by 15 columns × 12 rows pins ($d = 0.28$ mm), that is $D = 2\%$. It can be seen that there is a significant degradation on the fracture load when the loading rate is higher. This is different from the results of the big-pin reinforced DCB. Fig. 8a is an experimental load-displacement curve of a typical small-pin pullout test [15]. Different to the big-pin pullout shown in Fig. 4, there was a fast stress-drop upon reaching the maximum force which indicated pin debonding [15]. After that, the pins were pulled out against friction. The maximum debonding force and the maximum frictional pullout force are defined as P_d and P_f, respectively. Fig. 8b shows the results of σ_d and σ_f of a single pin calculated from P_d and P_f by pullout tests at different loading rates. It is clear that at a higher rate, the debonding stress is reduced but the frictional stress increased. Optical micrographs of z-pins after DCB testing are shown in Fig. 9. In contrast with the z-pins shown in Fig. 6, in

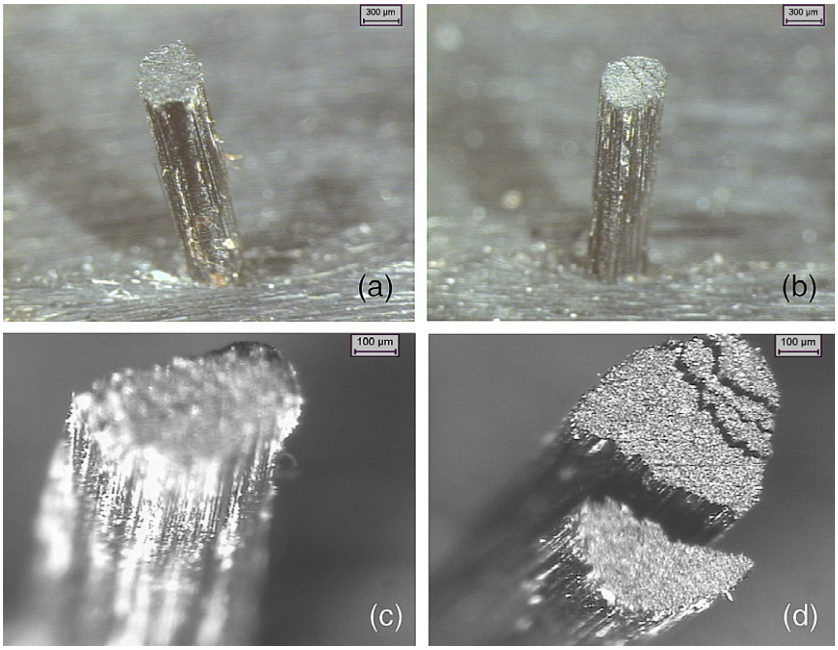

Fig. 6. Optical photomicrographs of z-pins after DCB delamination tests in which $d = 0.51$ mm, $D = 2\%$, (a) whole z-pin, $V = 1$ mm/min; (b) whole z-pin, $V = 100$ mm/min; (c) z-pin end, $V = 1$ mm/min; and (d) z-pin end, $V = 100$ mm/min. Splitting along length of pin due to shear failure is apparent at the high loading rate.

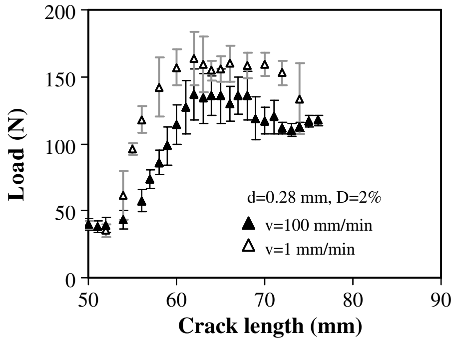

Fig. 7. Load-crack length curve of z-pinned DCB mode I delamination test, in which $d = 0.28$ mm, $D = 2\%$, $v = 1$ mm/min and 100 mm/min, respectively.

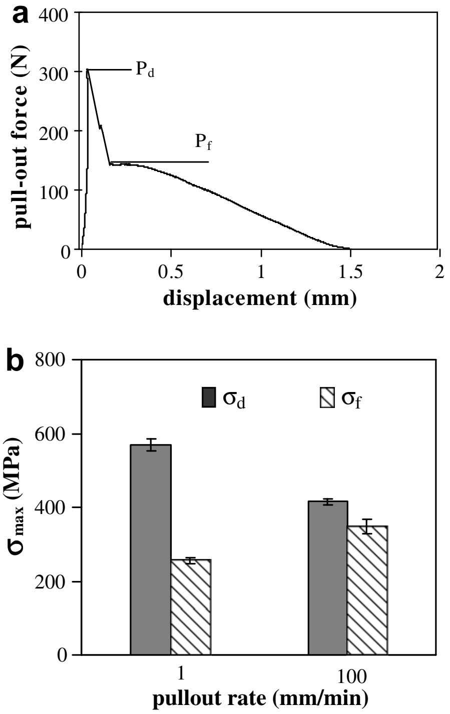

Fig. 8. (a) An experimental load–displacement curve of small-pin 3 × 3 pullout; (b) maximum bridging stresses of z-pin pullout test, in which, $d = 0.28$ mm, $v = 1$ mm/min and 100 mm/min, respectively. σ_d represents the maximum debonding stress and σ_f represents the maximum frictional stress after debonding.

Fig. 9a and b, the pins broke before being pullout, which indicates a different failure mode of z-pins against delamination growth. Since the pins rupture when the crack passes them, the effect of loading rate on the frictional stress (σ_f), see Fig. 8b, cannot be used to explain the results given in Fig. 7. As shown in Fig. 8b, before debonding, the pins can provide a higher bridging force at a lower loading rate. Therefore, in Fig. 7, a higher fracture load is needed for delamination growth at a lower loading rate.

Fig. 9c is a schematic illustration of a single pin which contains a bunch of T300 fibres. Theoretically, when the pin was under tension or bending, all interior fibres should break in the crack surface as the crack passed the pins. However, due to the non-uniform strength of the fibres, some fibres broke away from the crack plane. When the crack passed the pin, those broken fibres were pulled out from the matrix sockets in the beams. This is the reason why the z-pin ends shown in Fig. 9a and b are not flat. Compared to the whole pin pullout in big-pin DCB tests, the frictional bridging forces from those broken fibre pullout are negligible because of the short friction length and small contact area.

Comparison of the results of big-pin and small-pin samples (Fig. 10) shows the effect of loading rate on the z-pin bridging mechanism. From the histograms in Figs. 4 and 8b, it can be seen that, compared to the big pins, the small pins provide higher bridging stresses to the laminates during pullout. Thus, at similar interfacial strength, the small-pins can provide more efficient reinforcement to the DCBs against delamination [15]. As expected, in Fig. 10a, the fracture load of the small-pin sample is higher than that of the big-pin sample with the same density of z-pins. However, when the loading rate is high, as discussed in Section 2.3.1, the bending resistance from the big-pins and the "snubbing" friction become more prominent than that at the low loading rate. At the high loading rate, a big-pin reinforced DCB has higher delamination growth resistance. In contrast, because of their small moment of inertial of cross-section, the small pins cannot provide much resistant moment to the DCB. Moreover, when the crack has passed the small pins, they are virtually all ruptured and hence cannot provide further frictional resistance to the pullout. Hence, the fracture load of the small-pin reinforced DCB drops below the high loading rate curve because the debonding stress is reduced. As shown in Fig. 10b, the fracture load of the small-pin sample is lower than that of the big-pin sample when the loading rate is high.

2.4.1. Results of DCB samples with low density small-pin reinforcement

The results of the low density small-pin reinforced DCB tests are shown in Fig. 11, where the laminated beams were reinforced by 7 columns × 6 rows of pins ($d = 0.28$ mm), that is $D = 0.5\%$. It is shown that when the loading rate is higher, the fracture load is higher. In the tests, almost all pins were pulled out without breakage. Therefore, both the debonding stress $\sigma_d$and the frictional stress σ_f can affect the value of fracture load of DCB in Fig. 11. The results of the z-pin pullout in Fig. 8 show that the frictional pullout stress increases but the debonding stress decreases with increasing loading rate. The fracture loads shown in Fig. 11 indicate that in this case, the frictional pullout force plays a more dominant role in the delamination resistance. This finding is consistent with our numerical prediction presented previously in [6].

The cross-head displacement of DCB *versus* crack length of small-pin reinforcement is given in Fig. 12. Comparison

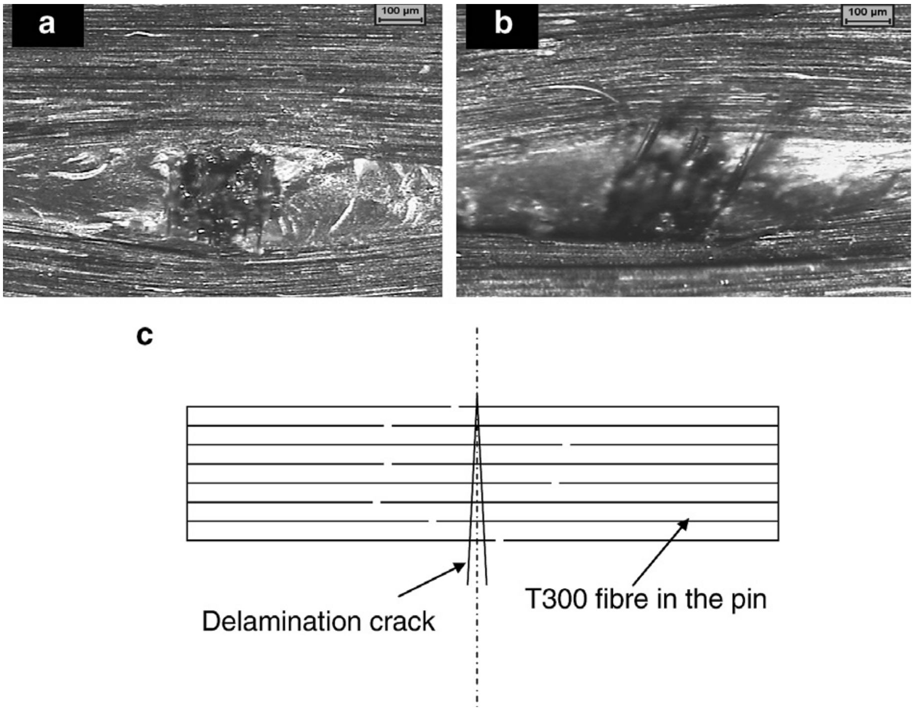

Fig. 9. Optical photomicrographs of z-pin ends after DCB delamination tests in which $d = 0.28$ mm, $D = 2\%$, (a) $V = 1$ mm/min; (b) $V = 100$ mm/min; and (c) a schematic of a single pin with broken T300 fibres.

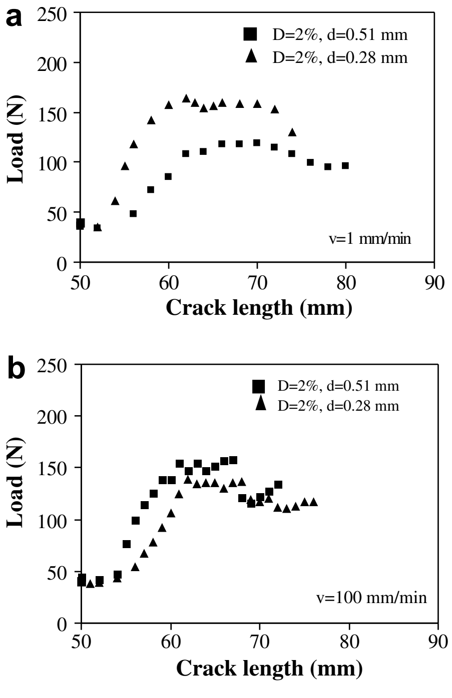

Fig. 10. Comparison of load-crack length curve of big- and small-pin samples under (a) low loading rate and (b) high loading rate, in which $D = 2\%$.

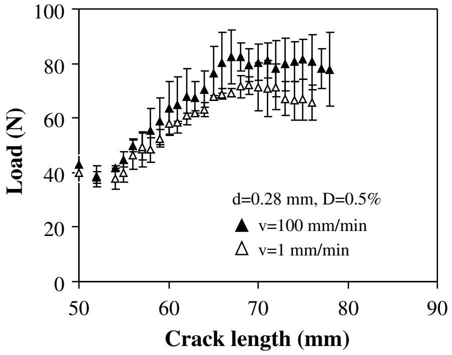

Fig. 11. Load-crack length curve of z-pinned DCB mode I delamination test, in which $d = 0.28$ mm, $D = 0.5\%$, $v = 1$ mm/min and 100 mm/min, respectively.

between Fig. 12a and b shows that the cross-head displacements of low density small-pin reinforced samples are much smaller than those of the high density z-pinned samples, whether the loading rate is high or low. These results imply that the bending resistance of DCB against delamination growth can be neglected when the density of z-pin is low. Furthermore, the large cross-head displacements of the DCB samples with high density small-pins suggest that these beams have endured very high bending moments during the delamination growth. This might be the reason why the pins in the high density small-pin reinforced DCBs ruptured during delamination. However, a quantitative evaluation of the bending stress on a single pin is required to gain a better understanding of this failure mechanism. In our future work, a theoretical model of z-pinned DCB delamination, in which the bending resistance from z-pins is taken into account, will be developed to examine the maximum tensile and shear stresses of a single z-pin during delamination growth under different loading rates.

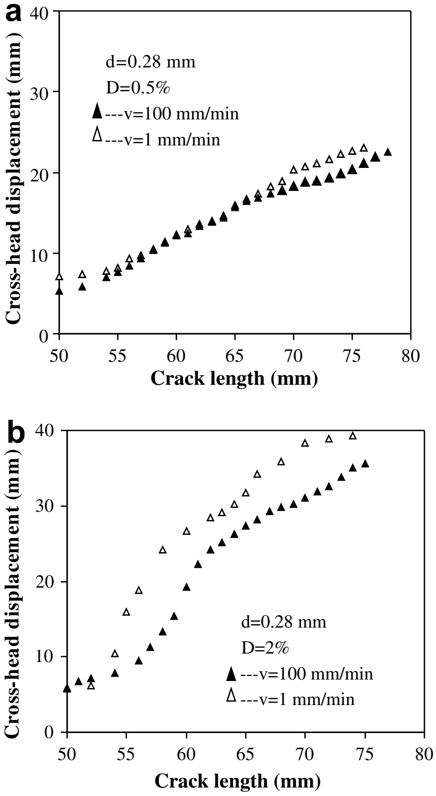

Fig. 12. Cross-head displacement of DCB versus delamination crack length of small-pin samples, in which, $v = 1$ mm/min and 100 mm/min, (a) $D = 0.5\%$, and (b) $D = 2\%$, respectively.

3. Concluding remarks

Mode I delamination tests on z-pinned DCB laminates were performed to evaluate the effects of loading rate on the z-pin bridging mechanisms. It is found that the loading rate has a noticeable effect on the fracture resistance and the z-pin reinforcement failure mode. From these experimental observations, the following conclusions were obtained:

(a) At a higher loading rate, a big-pin reinforced DCB shows a higher resistance against mode I delamination growth than at a lower loading rate because both bridging stress and bending moment are larger. But a higher loading rate produces more splitting damage in the pins.
(b) Z-pin pullout was not observed in high density small-pin reinforced DCB tests. All pins ruptured when the delamination crack passed by. The fracture resistance was higher at a lower loading rate than at a higher loading rate.
(c) During low density small-pin reinforced DCB delamination growth, all pins were pullout. The frictional pullout stress provided most resistance to the delamination. Since the maximum frictional stress increased with loading rate, the fracture load of DCB also increased when the loading rate was raised.

Despite the above observations and results, two questions remain unanswered. What causes the breakage of the z-pins in the high density small-pin reinforced samples? Why does the maximum friction stress increase with increasing loading rate? Could the latter be caused by the viscoelastic nature of the composite interface? With a high loading rate, this may increase the temperature during frictional sliding, which in turn changes the features of both the matrix resin and the interface between the z-pin and the laminates, and consequently, the bridging stress. Clearly, further studies on the effects of temperature and rate are needed to understand the physical mechanisms responsible for these experimental results.

It should also be noted that in this study only two rates were considered: 1 and 100 mm/min. Under these rates, the kinetic energy effect on crack-opening was small compared to that of the strain energy and could be ignored. At much higher loading rates, considerable increase of kinetic energy may weaken the effect of interfacial friction on the delamination behaviour and accelerate the delamination growth [14]. In contrast, a very low pullout rate may cause *stick-slips* during z-pin pullout [17], which may induce extra resistance to the delamination.

Acknowledgements

The authors thank the Australian Research Council for the continuing support of this project and the awards to Y.-W.M and H.-Y.L of an Australian Federation Fellowship and an Australian Research Fellowship, respectively, both tenable at the University of Sydney. Professor Ivana Partridge and Dr. Denis Cartié of Cranfield University kindly provided all the z-pinned composite samples for testing in this study. Their assistance is much appreciated.

References

[1] http://aztex-z-fiber.com.
[2] D.D.R. Cartie, Effect of Z-Fibre^{TM} on the Delamination Behaviour Carbon Fibre/Epoxy Laminates, PhD thesis, Cranfield University, 2000.
[3] D.D.R. Cartie, I.K. Partridge, Delamination behaviour of z-pinned laminates, in: Proceedings of ICCM12, 5–9 July, Paris, 1999.
[4] D.D.R. Cartie, I. K. Partridge, Delamination behaviour of z-pinned laminates, ESIS Publications, vol 27, Elsevier, 2000.
[5] H.-Y. Liu, Y.-W. Mai, Effect of z-pin reinforcement on interlaminar mode I delamination, in: Y. Zhang (Ed.), Proceedings of ICCM13, 25th–29th of June 2001, Beijing, China.
[6] H.-Y. Liu, W. Yan, Y.-W. Mai, Z-fibre bridging stress in composite delamination, in: B.R.K. Blackman, A. Pavan, J.G. Williams (Ed.), Fracture of Polymers Composites and Adhesives II, ESIS Publication 32, 2003, pp. 491–502.
[7] Yan W, Liu H-Y, Mai Y-W. Numerical study on the mode I delamination toughness of z-pinned laminates. Composites Science and Technology 2003;63:1481–93.
[8] Yan W, Liu H-Y, Mai Y-W. Mode II delamination toughness of z-pinned laminates. Composites Science and Technology 2004;64:1937–45.
[9] Cox BN. A constitutive model for through-thickness reinforcement bridging a delamination crack. Advanced Composites Letters 1999;8(5):249–56.

[10] Rugg KL, Cox BN, Massabo R. Mixed mode delamination of polymer laminates reinforced through the thickness by z-fibres. Composites Part A 2002;33:177–90.
[11] Cartié DDR, Cox BN, Fleck NA. Mechanisms of crack bridging by composite and metallic rods. Composites Part A 2004;35(11):1325–36.
[12] Glennie EB. Strain-rate dependent crack model. Journal of Mechanics and Physics of Solids 1971;19(5):255–72.
[13] Hellan K. Debonding dynamics of an elastic strip, I: Timoshenko-beam properties and steady motion. International Journal of Fracture 1978;14(1):91–100.
[14] Sridhar N, Massabo R, Cox BN. Delamination dynamics in through-thickness reinforced laminates with application to DCB specimen. International Journal of Fracture 2002;118(2):119–44.
[15] Dai S-C, Yan W, Liu H-Y, Mai Y-W. Experimental study on z-pin bridging law by pullout test. Composites Science and Technology 2004;64:2451–7.
[16] P. Chang, AP. Mouritz, BN. Cox, Properties and failure mechanisms of z-pinned laminates in monotonic and cyclic tension, Composites A, in press.
[17] Povirk GL, Needleman A. Finite element simulations of fibre pullout. Journal of Engineering Materials and Technology 1993;115:286–91.