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Experimental Study On Z-Pinned DCB Mode I Delamination

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ABSTRACT: An experimental investigation on mode I delamination of z-pinned double-cantilever-beams (DCB) and corresponding pin pullout behaviour is presented. The effects of loading rate on delamination crack opening and z-pin bridging mechanisms is reported. Optical micrographs of z-pins after pullout show that a higher loading rate causes more splitting damage in the pins. Comparison of fracture load shows that the fracture load rises with increasing loading rate. Z-pin pullout tests were also conducted to give a detailed description of z-pin bridging mechanisms.

1. INTRODUCTION

Z-pin, *also called Z-Fiber*^{TM}, (see Aztex website) is a novel technique which was developed to increase the strength of laminated composites in the thickness direction, that is, z-direction. Recent studies have confirmed that z-pinning greatly improves the fracture toughness of reinforced composites against interlaminar delamination. Its performance under typical Mode I, Mode II and mixed Mode I/II loading were studied experimentally and numerically [Cartie, 2000; Yan et al 2003; Yan et al, 2004]. Fig. 1 shows a double-cantilever-beam (DCB) specimen with z-pin reinforcement. During Mode I delamination, a reinforcing z-pin provides a closure force to the opening crack. The efficiency of z-pinning is strongly dependent on the corresponding bridging mechanisms [Liu et al, 2003]. The functional relationship between delamination crack-opening and closure force from a single pin is called the “bridging law”, which can be evaluated in principle by a z-pin pullout test [Dai et al, 2004]. As reported in earlier studies, the pullout behaviour of a single fibre can be affected by the loading rate [Liu et al, 1999]. A high pullout rate can reduce both debonding force and friction coefficient [Chai et al, 1996; Povirk et al, 1993]. With rapid expansion of applications of composites, composite structures often face rather complex in-service conditions, one of which is the effect of loading rate. The bridging mechanisms of z-pin reinforcement under different loading rates must hence be critically evaluated before any further development of this new technique can be advanced. But, to-date, no rigorous theoretical models and no experiments on this special topic have been published.

This paper presents an experimental study on the effects of loading rate on z-pinned DCB mode I delamination fractures. Loading rates of 1 and 100 mm/min were chosen and the corresponding load-displacement curves were obtained. Optical photos of z-pin microstructure after pullout were provided to examine the z-pin damage under different loading rates. Tests were carried out for two types of samples: small pin reinforcement with an areal density of 0.5% and big pin reinforcement with an areal density of 2%. The results show that 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 confirm the conclusion obtained from the DCB tests.

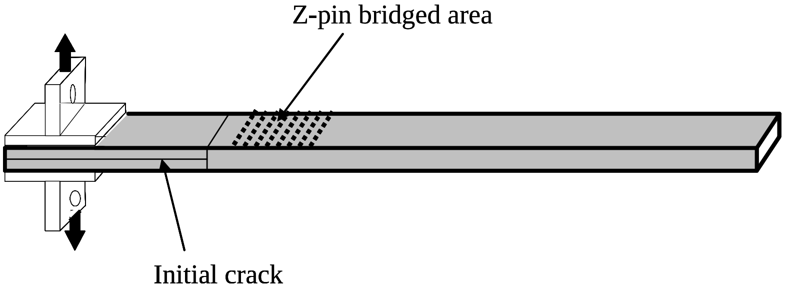
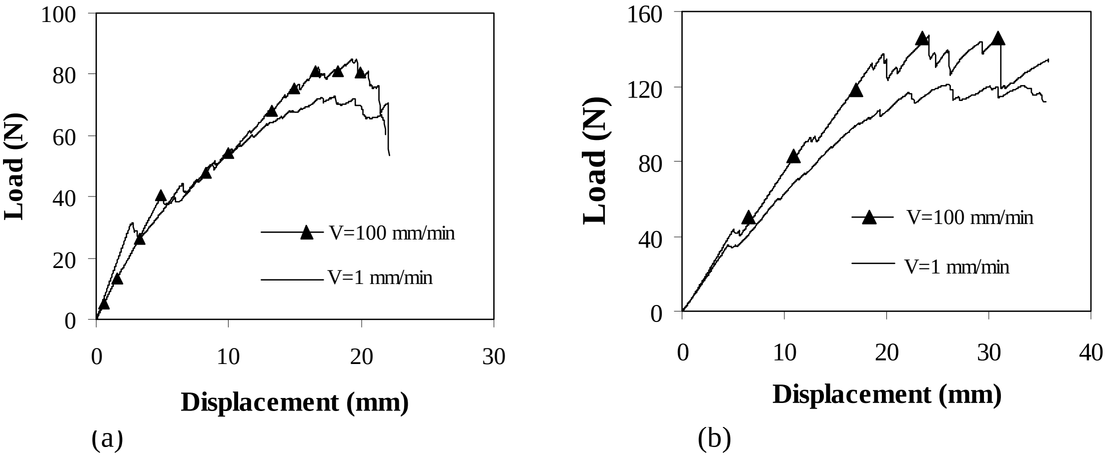


Figure 1. DCB specimen with z-pinning reinforcement.

2. EXPERIMENTAL PROCEDURE AND RESULTS

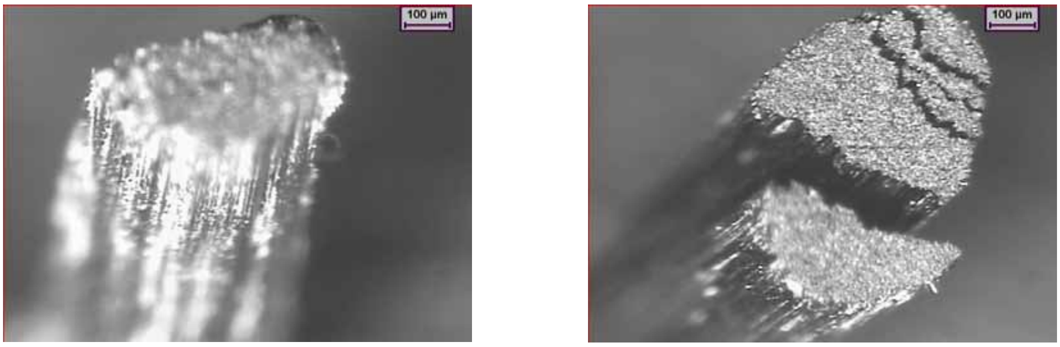
2.1 Z-pinned DCB tests

The experimental configuration for the z-pinned DCB mode I test is shown in Figure 1, in which the z-pins were made of carbon fibre (T300) reinforced BMI resin. The laminated beams were made of carbon fibre (IMS) reinforced epoxy (924) with dimensions: 150mm in length, 20 mm in width and 1.5 mm in thickness. The z-pins were vertically inserted into the beams by an ultrasonic insertion machine before curing [Cartie, 2000]. A thermal insulation 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 crosshead speeds (V) of either 1 or 100 mm/min. Load-displacement traces were recorded until the delamination crack propagated along the full length of the beams. 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. Two types of samples were tested. Figure 2(a) shows load-displacement curves of small pin reinforced DCB delamination, in which the z-pin diameter, d, is 0.28 mm and the areal density, D, is 0.5% (7 columns×6 rows). It is shown that at a higher loading rate, a larger applied load was needed to spread the delamination. The results of big pin reinforced DCB delamination tests are shown in Figure 2(b), where the laminated beams were reinforced by 8 columns×6 rows big pins (d=0.51 mm), that is D=2%. It can be seen that the results agree with those in Fig. 2(a) from small pin tests, i.e., they confirm the effect of loading rate on the delamination crack opening.



(a) (b)

Figure 2. Load-displacement curve of mode I DCB tests under loading rates of V=1 mm/min and V=100 mm/min, in which (a) d=0.28 mm, D=0.5% and (b) d=0.51 mm, D=2%.



(a) (b)

Figure 3. Optical photos of z-pin ends after DCB delamination tests in which d=0.51 mm, D=2%; (a) V=1 mm/min and (b) V=100 mm/min. Splitting along length of pin due to shear failure is apparent at the high loading rate. Magnification is 50x.

Results from the above tests seem to be inconsistent with previous studies [Liu et al, 1999; Chai et al, 1996; Povirk et al, 1993] in which it was predicted that the pullout force of a single fibre would decrease with increasing loading rate. To understand loading rate effect on the bridging mechanisms of z-pins, optical photomicrographs of typical z-pin ends after pullout were taken with a WILD Heerbrugg microscope, as shown in Figure 3, for the two different loading rates and d=0.51 mm, D=2%. It can be seen that when the loading rate is low, the z-pin pulls out without any obvious damage. However, when the loading rate is high, the z-pin is pulled out accompanied by a number of splits along the length of the pin, which may be caused by the high rate shearing during both pullout and bending of the beams. At a high loading rate, the cross-head displacement of the beam was increased at a very high rate which was 100 times higher than that at the low loading rate test. However, the delamination crack could not propagate at the same rate due to the resistance imposed by the z-pins. At a given crack length, the curvature of the beam under a high loading rate was hence larger than that under a low loading rate. That means, z-pins under a high loading rate suffered more severe bending before being pullout which caused splitting damage in the z-pins as shown in Figure 3(b). Consequently, the resistance to bending of z-pins delayed the delamination propagation. A higher applied load was required for further crack growth. In the meantime, 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 the pin pullout. As reported by Liu et al [Liu et al, 2003], z-pin bridging force due to frictional pullout contributes significantly to the delamination resistance. As shown in Figure 2, a higher load is needed for crack growth when the loading rate is higher.

2.2 Z-pin pullout tests

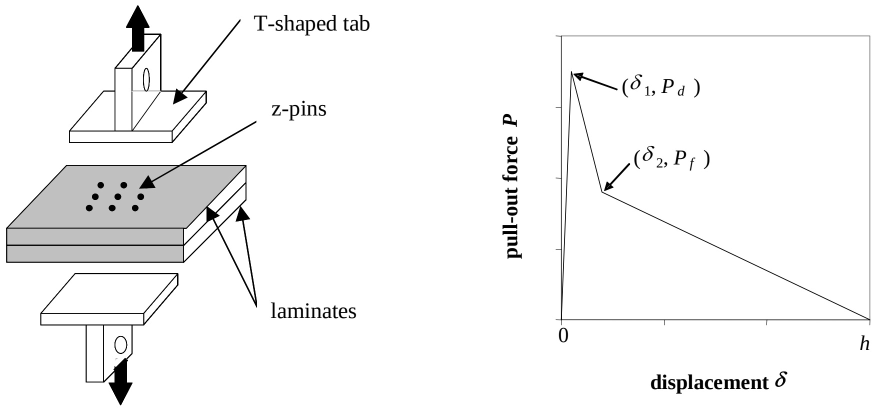


Figure 4. (a) Illustration of experimental configuration for 3×3 z-pins pull-out tests; (b) a simplified tri-linear bridging law in z-pinned DCB mode I delamination [Liu et al, 2003].

Z-pin pullout tests as shown in Figure 4(a) were carried out to study the relationship between the bridging force and the pullout displacement under different loading rates. Details of experimental procedure and samples were given in our earlier paper [Dai et al, 2004]. Generally, a complete pull-out procedure includes three stages, which can be described by a tri-linear bridging law as shown in Figure 4(b). The bridging law can be characterised by four parameters: maximum debonding force P_d, maximum frictional force P_f and corresponding displacements δ_1, δ_2 [Liu et al, 2003]. In the first stage, with increasing applied displacement, the pullout force increases rapidly until it reaches a peak value, P_d. Then, in the second stage, the pin debonds from the laminates and the load drops very rapidly to a value P_f, with a very small increase of displacement. In the third stage, the load gradually reduces to zero with frictional pullout. Figure 5(a) shows the results of maximum debonding force P_d and maximum frictional force P_f of 3×3 small pins (d=0.28 mm) pullout tests. The pin-to-pin distance is 3.51 mm that represents D=0.5%. The loading rates were set at 1 and 100 mm/min. The values given in Figure 5 are the total force applied to the nine pins. It can be seen that under a high loading rate, the debonding force is reduced. It indicates that the adhesive strength is significantly degraded by the loading rate, which is consistent with Chai et al's results [Chai et al, 1989, Liu et al, 1999]. However, in a z-pin pullout test, nine pins were inserted into two laminates before curing. During the insertion, a small amount of misalignment always occurred in some pins, (i.e., some pins were not perfectly perpendicular to the laminates). When the pullout load was applied to the laminates, these misaligned pins were bent in addition to being pulled by tension. As we discussed in the previous section, a high rate load caused a larger bending on the z-pins. Therefore, the resistance from the bent pins and also the corresponding "snubbing" friction were larger when the loading rate was higher. Figure 5(a) shows the maximum frictional force to increase with increasing loading rate. This result confirms the DCB tests results given in Figure 2(a).

The results of big pins pullout are given in Figure 5(b), in which 3×3 big z-pins (d=0.51 mm) were used. The pin-to-pin distance is 3.10 mm that represents D=2%. The loading rates were also set at 1 and 100 mm/min. The load-displacement curves were taken until the pins were completely pulled out. Since the load-drop due to debonding rarely appeared in the big pin pullout tests [Dai et al, 2004], only the results of maximum frictional load are shown. It is also proven that the friction load increases with rising loading rate. These results are in agreement with those of DCB tests shown in Fig. 2(b) and the optical photos shown in Figure 3.

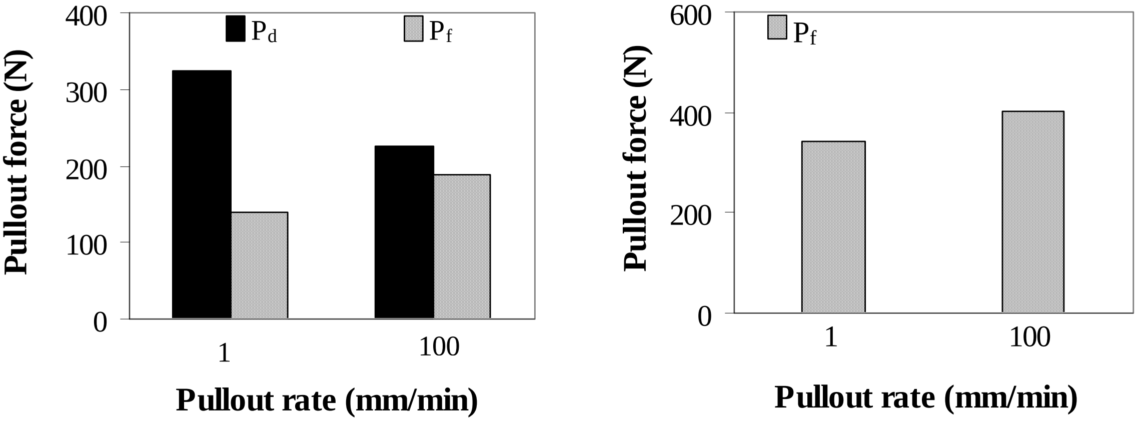


Figure 5. (a) Maximum debonding force and maximum frictional force of 3×3 small pin pullout, in which, d=0.28 mm and D=0.5%; and (b) maximum frictional pullout force of 3×3 big pin pullout, in which, d=0.51 mm and D=2%.

3. CONCLUSION

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 under different loading rates, the bridging mechanisms are different. Under a high loading rate, the z-pins experience both tension and bending due to a rapid increase of DCB curvature. As a result, the pins were always pulled out accompanied by serious splitting along their lengths due to shear failure. Moreover, bending of the pins against the laminates provided an additional "snubbing" friction to deter delamination growth. Thus, the fracture load increased when the loading rate was high. Results of pullout tests showed that the adhesive strength between z-pins and laminates was degraded by loading rate. As a result, the debonding force was significantly decreased when the loading rate was increased. But a higher loading rate caused more splitting damage inside the pin and an additional snubbing friction against the laminates so that the bridging force was increased.

It should 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 can be ignored. At higher loading rates, considerable increase of kinetic energy may weaken the effect of interfacial friction on the delamination behaviour and accelerate delamination growth. In contrast, a very low pullout rate may cause *stick-slips* during z-pin pullout [Povirk et al, 1993], which may cause an extra resistance to delamination growth. To provide a complete study of loading rate effects on z-pin bridging mechanisms, further work must be conducted.

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