DYNAMIC BRIDGING RESPONSE OF THROUGH-THICKNESS REINFORCEMENT IN COMPOSITE LAMINATES

Hao Cui[1], António R. Melro[2], Yusuf Mahadik[2], Mehdi Yasaee[3], Giuliano Allegri[4], Ivana K. Partridge[2], Stephen R. Hallett[2], Nik Petrinic[1]

[1] Department of Engineering Science, University of Oxford, UK

[2] Bristol Composites Institute (ACCIS), University of Bristol, UK

[3] Centre for Structures, Assembly and Intelligent Automation, Cranfield University, UK

[4] Faculty of Aeronautics, Imperial College of London, UK

ABSTRACT

The present experimental study aims to extend the understanding of delamination crack bridging mechanisms in Z-pinned laminates subjected to highly dynamic loading conditions. The bridging response of single Z-pins was characterized with both quasi-static and high loading rate. Standard delamination tests of Z-pinned laminates were carried out at varying velocity. The experimental results at both length scales showed that Z-pin efficiency in improving delamination resistance decreases with increasing loading rate.

KEYWORDS: Z-pinning; Dynamic; Delamination; Fracture toughness; Bridging response

1. INTRODUCTION

Delamination damage is one of the most critical issues in the design and analysis of laminated composite structures [1, 2]. Z-pinning is one means of through-thickness reinforcement to mitigate against delamination propagation [3]. The technique consists of placing thin rods made from carbon fibre reinforced epoxy or metal to improve the apparent fracture toughness of the composite in the through-thickness direction. Work done to date to characterise z-pin behaviour has largely been conducted under quasi-static conditions [3-7].

In practical applications, Z-pinning is often used to mitigate the effects of damage induced by impact loading, and composite structures are frequently threatened by impact loading [8, 9]. However, current understanding of Z-pinning failure mechanisms is still limited to the quasi-static loading regime. In this paper, we conducted the first systematic study on the dynamic bridging response of Z-pins at two distinct length scales. The single pin bridging response was directly characterized, and the standard delamination experiments of Z-pinned laminates were conducted as well. The experimental setups are introduced in Section 2; all results and discussions are presented in Section 3.

2. EXPERIMENTS

2.1 Single pin tests

The crack bridging response can be measured by testing small blocks of composite laminates containing Z-pins. As shown in Fig.1, the sample containing an array of 4x4 Z-pins reinforcing the pre-delaminated IM7/8552 prepreg laminate has been characterised at loading rates ranging from 0.01 mm/s to 6 m/s, using a screw-driven ZWICK testing machine and a split Hopkinson tensile bar (SHTB) apparatus [10]. The angle between the Z-pin specimen axis and the loading axis, β, was varied to span a range of shear-to-opening displacement ratios, to represent mixed mode delamination of Z-pinned laminates. The angle was controlled by bonding the Z-pinned samples to aluminium fixtures with different wedge angles. A brass sleeve was used to constrain the lateral displacement of the samples. The high-speed Kirana camera was used to capture the deformation and failure process in all experiments with frame rate of up to 500,000 fps. The images were analysed with digital image correlation (DIC) method to estimate the opening and shear displacements applied to the Z-pins. The force measured from the ZWICK testing machine and SHTB was synchronized with the displacement analysed using DIC to compile the Z-pin bridging response.

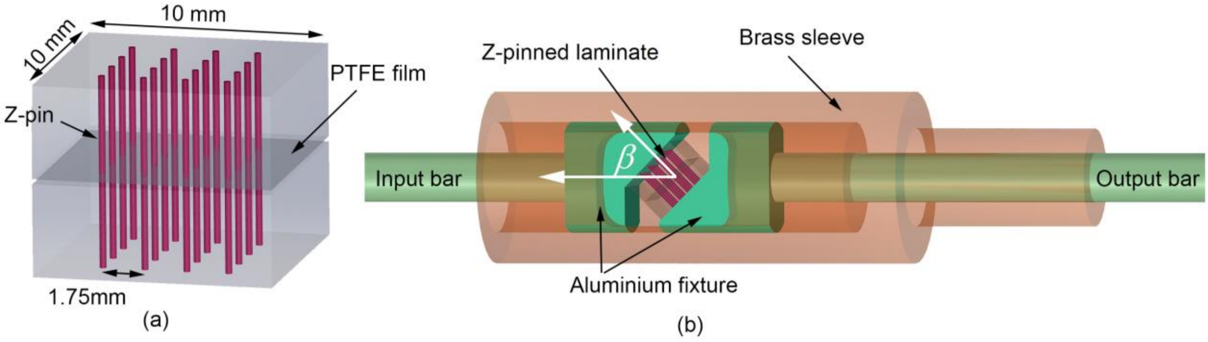

Fig.1. (a) Z-pinned composite laminate sample, (b) mixed mode experiment configuration

2.2 Delamination test

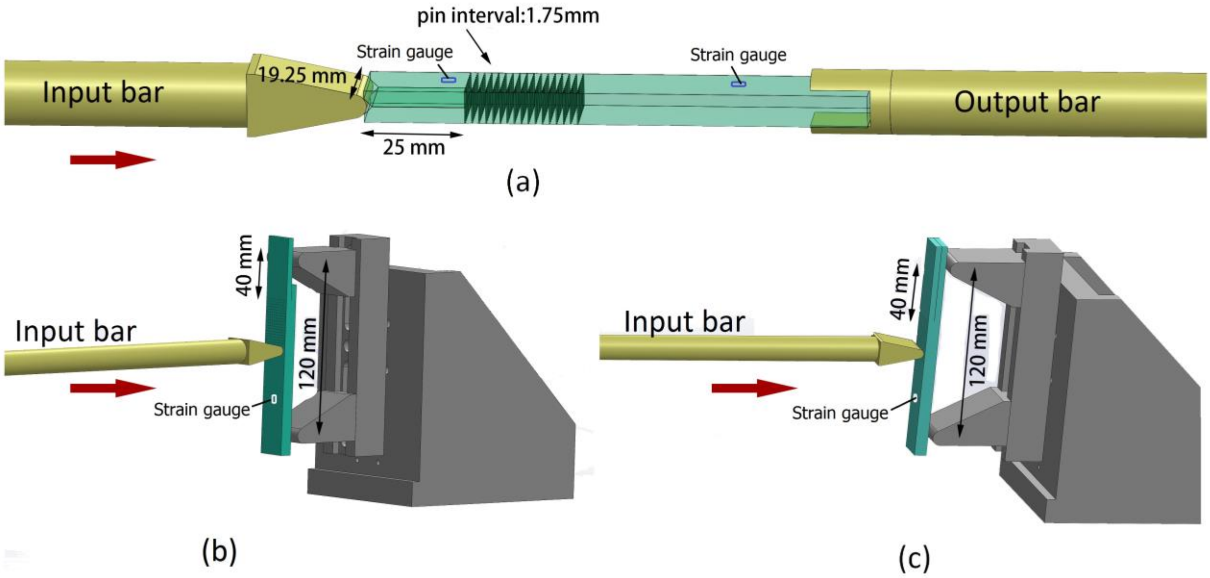

Fig.2. Dynamic delamination tests using split Hopkinson pressure bar:(a) mode I wedge opened double cantilever beam test; (b) single leg bending test; (c) end notched flexure test.

Single pin tests were able to characterize the Z-pin properties at the meso-scale, where the laminates were completely pre-cracked to get the pure Z-pin bridging force, and the interaction between delamination failure and Z-pin bridging was ignored. Delamination tests of Z-pinned laminates were more representative for the performance of practical structures. In this paper, mode I, mode II and mixed mode delamination tests have been carried out. The composite laminates were made of IM7/8552 prepregs with a layup of [[0°/-45°/0°/45°] 4s]s, and the nominal thickness of the laminates was 8mm. The laminates were pre-cracked with 13 μm thick PTFE film, without any further pre-cracking [11] to prevent changing the microstructures within and around Z-pins before delamination tests. As sketched in Fig. 2a, the Z-pin array was placeed in front of the initial crack tip, which included 11 pins across the beam width and 17 pins in the longitudinal direction. Unpinned laminates were prepared as well to be used as benchmarks.

The Wedge opened Double Cantilever Beam (WDCB) was used for mode I delamination test, as shown in Fig. 2a. The edge of the laminates was chamfered to introduce the lateral opening force in the beginning of the test. The Single Leg Bending (SLB) test was employed to generate the mixed mode dynamic delamination. For the samples with symmetrical layups and loaded at the mid-span of the beam, the mode mix ratio GII/GM was around 0.32. The mode II delamination tests were carried out using the End Notched Flexure (ENF) configuration. Both unpinned and Z-pinned samples were tested for all these configurations, with varying displacement loading rates. The quasi-static tests were done on the screw-driven ZWICK testing machine. A Split Hopkinson pressure bar was used to test the samples at high loading rate. 1 mm thick rubber film was used as pulse shaper to create a smooth raising edge on the compressive pulse. The rubber film was also placed between the impactor nose and the sample to reduce the vibration of the laminates.

Due to the significant mismatch in the impedance between the sample and the bars, the force in dynamic tests was not able to be accurately measured with the traditional Hopkinson bar theory [12]. Strain gauges were attached on the back of the composite laminates in this work, and classical beam theory was used to calculate the force.

3. RESULTS AND DISCUSSIONS

3.1 Single pin results

The evolution of the bridging force under pure mode I (β =0°) and under a mixed mode (β =30°) displacement is presented in Fig. 3(a). In mode I, the bridging force initially increased rapidly up to the interfacial shear failure between Z-pins and laminate, thus causing a sudden drop in bridging force. The Z-pins were then pulled out from the laminate, providing considerable bridging force due to friction along the failed interface. When loaded rapidly, this frictional bridging force was much lower than that in the quasi-static case. This may be due to rate dependent failure morphology and frictional conditions. In the mixed mode, the Z-pins fractured at a lower displacement than that in pure mode I (Fig. 3(a)), before any frictional resistance to pulling-out the Z-pins could make a significant contribution.

The energy dissipation for a single pin was calculated by integrating the area under the bridging force-displacement curves and then dividing it by the number of pins in the specimen. As shown in Fig. 3(b), as mode mixity increased, the energy dissipation initially grew with increasing angle β, due to the additional friction between the pin and the surrounding matrix caused by lateral pin deformation. Further increase in angle β resulted in a significant drop in energy dissipation, as the pins started to split and rupture instead of being completely pulled out.

The Z-pin efficiency appears to decrease with increasing loading rate most significantly for mode I delamination loading, with minimal rate effects being observed for $\beta > 30°$, i.e. when the pins start to fail before being completely pulled out. The energy dissipation in mode I delamination is dominated by the frictional pulling-out of pins, and is largely influenced by the interface morphology between the pin and surrounding materials. The change of fracture surface with loading rate, was found to be responsible for the decreased Z-pin efficiency in dynamic cases [13].

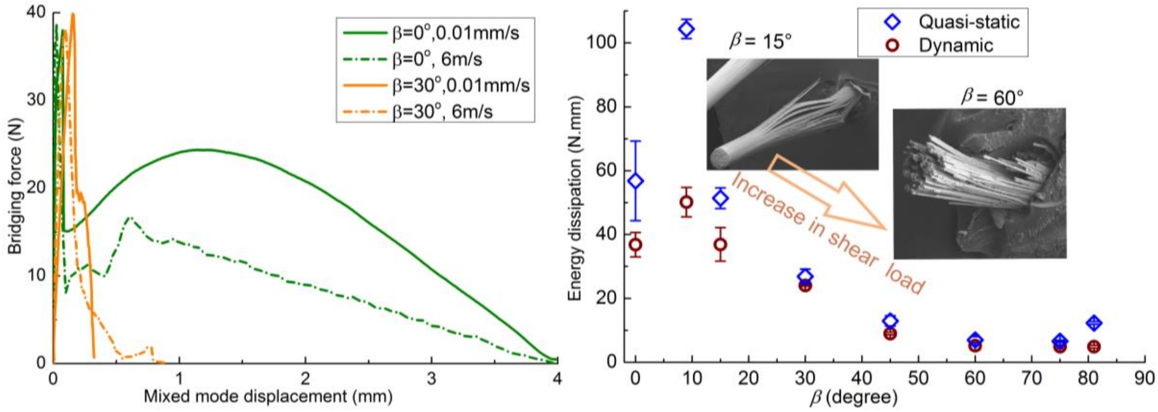

Fig.3. (a) Representative bridging force-displacement curves; (b) Energy dissipation of Z-pins and the change in Z-pin failure mode.

3.2 Delamination test results

The lateral force responsible for opening the WDCB sample was obtained using the bending strain on the back of laminates, and plotted in Fig. 4a as function of wedge displacement. The crack initiated at similar force for both unpinned and Z-pinned samples. The force after crack initiation decreased gradually for unpinned ones, and no significant influence of loading rate was noticed; it kept increasing when Z-pins were present, and it was higher in quasi-static test than that in dynamic one. The WDCB samples lost its loading capacity at around 3 mm in unpinned case, while complete failure was only reached after a displacement of 14 mm in dynamic tests with Z-pinning.

The critical force for delamination initiation was also found to be independent of the Z-pinning in SLB tests. The force increased for all samples during the growth of crack, because of the considerable bending stiffness of delaminated laminates. The delamination resistance was improved by Z-pinning in this mix mode tests, and the Z-pinning efficiency was found to decrease slightly with increase in loading rate.

Unstable crack propagation was observed in the mode II tests of both unpinned and Z-pinned laminates. The crack initiated from the edge of PTFE film, and the resin rich pocket in front of the initial crack tip may stimulated the instability after the onset of crack. The Z-pinned samples showed smaller drop in load compared with unpinned ones, however, the improvement to mode II delamination resistance is moderate, and was not significantly influenced by loading rate.

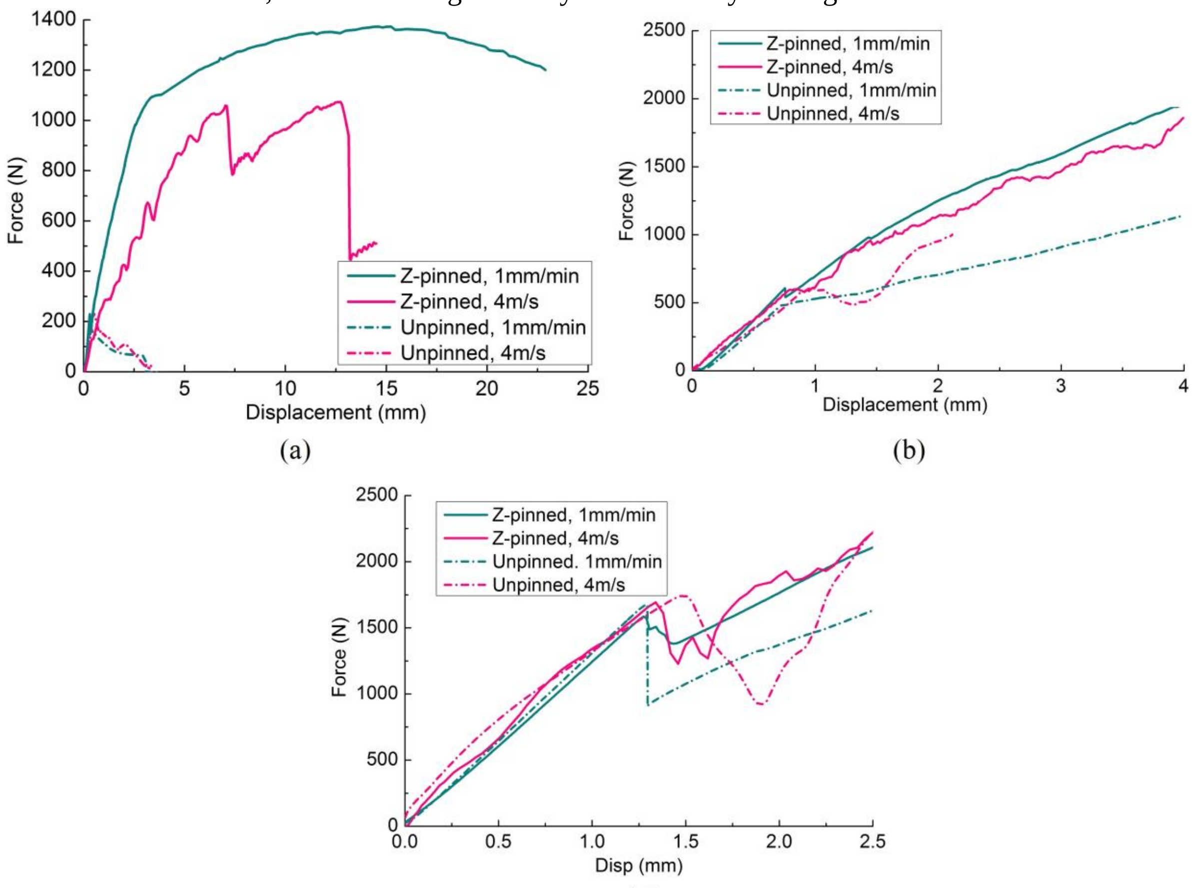

Fig. 4. Representative force-displacement curves from both unpinned and Z-pinned samples at two different loading rates: (a) WDCB tests; (b) SLB tests; (c) ENF tests.

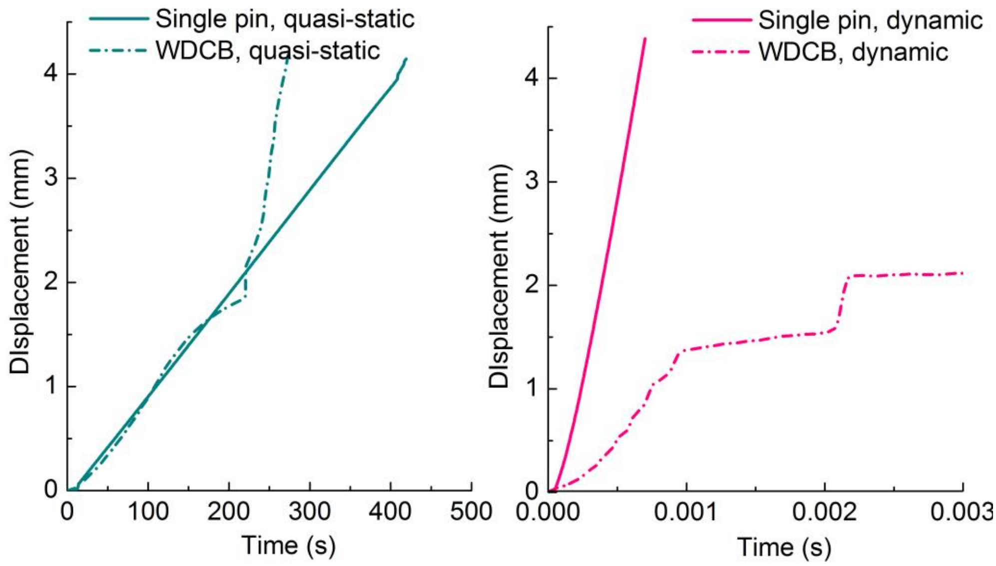

Fig. 5. Local opening displacement of Z-pins in both WDCB and single pin tests.

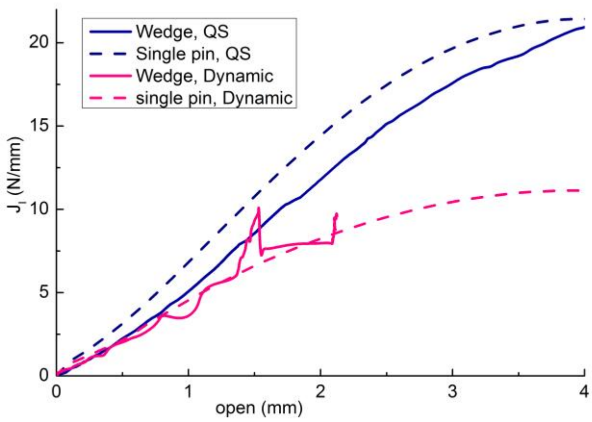

Fig. 6. The fracture toughness plotted as a function of deformation at initial crack tip.

3.3 Discussions

The single pin tests revealed that the efficiency of Z-pinning in improving the toughness of composite laminates is higher in mode I dominated delamination than that in mode II, and it decreases with loading rate. As shown in Fig. 5, the local loading rate on the Z-pins in front of the initial tip of WDCB sample was comparable with that of single pin sample in quasi-static tests. The dynamic WDCB tests provided lower pull-out rate than that of dynamic single pin tests. The force-displacement curves from WDCB, SLB and ENF tests showed the same rate dependence as observed in single pin tests.

Because of the large bridging zone at the crack front, the traditional data processing methods based on linear fracture mechanics theory cannot be used to estimate the delamination resistance of Z-pinned laminates. Alternatively, J-integral methods [14] was employed in this paper, and the mode I results was shown in Fig.5. The bridging response of single pin at β of 0° shown in Fig.2a was integrated to get the energy dissipation, and the energy dissipation was divided by the laminate area per each pin (1.75mm ×1.75 mm) to get the approximate delamination toughness, the contribution from delamination of unpinned laminates was neglected here since its value is much lower than from Z-pins alone. As shown in Fig. 6, both single pin tests and WDCB provided similar results for both loading rates. The good agreement between these two types of experiments confirmed the validity of single pin tests.

4. CONCLUSIONS

This is the first detailed reporting of the effect of high rate loading on the failure mechanisms and bridging force of Z-pins in a carbon-fibre/epoxy laminate, representing lay-ups of typical critically loaded components. It can be concluded that Z-pinning is more efficient in improving the mode I dominated delamination resistance than that in mode II. The Z-pinned composite laminates have lower inter-laminar mode I performance when loaded at higher velocity. Understanding the dynamic response of Z-pins is important for the design and analysis of through-thickness reinforced composite laminates subjected to impact loading.

ACKNOWLEDGEMENT

This research was supported by EPSRC funding in the UK (grant no EP/M012905/1).

REFERENCES

[1] Davies GAO, Zhang X. Impact damage prediction in carbon composite structures. Int J Impact Eng. 1995;16:22.
[2] Schoeppner GA, Abrate S. Delamination threshold loads for low velocity impact on composite laminates. Composites Part A: Applied Science and Manufacturing. 2000;31:13.
[3] Mouritz AP. Review of z-pinned composite laminates. Composites Part A: Applied Science and Manufacturing. 2007;38(12):2383-2397.
[4] 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(16):2451-2457.
[5] Cartié DDR, Cox BN, Fleck NA. Mechanisms of crack bridging by composite and metallic rods. Composites Part A: Applied Science and Manufacturing. 2004;35(11):1325-1336.
[6] Rugg KL, Cox BN, Massabo R. Mixed mode delamination of polymer composite laminates reinforced through the thickness by Z-fibers. Composites Part A: Applied Science and Manufacturing. 2002;33.
[7] Rugg K. L CBN, Sherrick G. O. Damage mechanisms for angled through-thickness rod reinforcement in carbon–epoxy laminates. Composites Part A: Applied Science and Manufacturing. 1998;29A.
[8] Quaresimin M, Ricotta M, Martello L, Mian S. Energy absorption in composite laminates under impact loading. Composites Part B: Engineering. 2013;44(1):133-140.
[9] Abrate S. Impact on Laminated Composite Materials. Applied Mechanics Reviews. 1991;44(4):46.
[10] Gerlach R, Kettenbeil C, Petrinic N. A new split Hopkinson tensile bar design. Int J Impact Eng. 2012;50:63-67.
[11] International A. Standard Test Method for Determination of the Mode II Interlaminar Fracture Toughness of Unidirectional Fiber-Reinforced Polymer Matrix Composites. D7905/D7905M-14, vol. PA 19428-2959 United States: ASTM International; 2014.
[12] Zhao H. Material behaviour characterisation using SHPB techniques, tests and simulations. Comput Struct. 2003;81(12):1301-1310.
[13] Cui H, Yasaee M, Kalwak G, Pellegrino A, Partridge IK, Hallett SR, et al. Bridging mechanisms of through-thickness reinforcement in dynamic mode I&II delamination. Composites Part A: Applied Science and Manufacturing. 2017;99:198-207.
[14] Cui H, Koussios S, Li Y, Beukers A. Constitutive law of adhesive layer measured with mixed mode bending test. Engineering Fracture Mechanics. 2014;127:235-251.

Dynamic bridging response of through-thickness reinforcement in composite laminates

Cui, Hao

2017-12-31