Zhang, B., Allegri, G., & Hallett, S. R. (2015). Through-thickness sensing of single Z-pin reinforced composite laminates. In Proceedings of the 20th International Conference on Composite Materials (ICCM20). [1203-2] International Conference on Composite Materials, ICCM.

THROUGH-THICKNESS SENSING OF SINGLE Z-PIN REINFORCED COMPOSITE LAMINATES

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Keywords: Delamination, Multifunctional composites, Sensing, Z-pins

ABSTRACT

This paper investigates the through-thickness sensing behaviour of carbon/BMI Z-pin reinforced composite laminates. The through-thickness electrical resistance (TTER) is used as the sensing variable. Electrodes are bonded to the Z-pin ends and the TTER is measured employing a sensor reading and analysing (SRA) system. The SRA system consists of a multiplexer, a digital multimeter, communication modules and a PC running the National Instruments LabVIEW program for the control of the whole system and the TTER data acquisition. The sensing capability of through-thickness reinforced laminates is characterised via single Z-pin bridging tests, carried out in Mode I and Mode II. The experimental results show that the whole Mode I pullout process of Z-pins can be monitored via the TTER variation. In mode II, no actual pullout occurs and the Z-pins experience failure while bridging the delamination. However, the Z-pin failure event is detectable as a sudden increase of the TTER. This study demonstrates that carbon/BMI Z-pins can be successfully employed in multi-functional applications involving simultaneous delamination bridging and structural health monitoring.

1 INTRODUCTION

Z-pinning is an effective through-thickness reinforcement technology for composite laminates. Z-pins are small diameter composite or metal rods, which are usually inserted perpendicularly to the mid-plane of a composite laminate [1]. Z-pinning has been extensively investigated since its introduction back in 1990s. Experimental and numerical studies have addressed both the bridging response of individual Z-pins [2–5] and fracture toughness enhancement of laminates reinforced with Z-pin arrays [6–8]. It has been demonstrated that Z-pins can effectively delay or arrest delamination propagation under quasi-static, impact and fatigue loadings, albeit there exists a trade-off between interlaminar toughness enhancement and the resulting laminate in-plane stiffness and strength properties.

It has been demonstrated that carbon-fibre laminates have self-sensing capability based on ER measurement [9,10]. However, research on sensing capability of Z-pin reinforced laminates is still missing. The most widely employed Z-pins are small-scale carbon-fire reinforced composites which lend themselves to use as sensors. The sensing performance of laminates may be modified or enhanced due to the presence of Z-pins. Therefore, it is worth studying the sensing function of laminates reinforced by Z-pins. As a preliminary study, this paper investigates the through-thickness sensing behaviour of Z-pinned laminates via single Z-pin bridging tests. The study is performed based on monitoring the TTER values under Mode I and Mode II loadings. Experiment results demonstrate that the through-thickness reinforcement elements can be employed successfully as sensing units for reinforced laminates.

2 SAMPLE PREPARATION

The coupons used in this study had the configuration shown in Fig. 1. They consisted of a laminate split in half by a PTFE release film. A single T300/BMI Z-pin was inserted through the thickness of the laminate, and two silver/epoxy electrodes were bonded to the ends of the Z-pin. The laminate was manufactured using 48 IM7/8552 plies (Hexcel, UK) with stacking sequence $[(-45/90/45/0)s]_6$. The coupons had in-plane dimension of 20mm × 20mm and a total thickness of 6mm. The Z-pin diameter was 0.28mm. The electrodes were attached to both the Z-pin ends and the laminate top and bottom surfaces. Each electrode has the thickness of 1mm and in-plane dimension of 5mm × 5mm. This gave a Z-pin nominal length at 8mm. In addition, the electrodes were wired for electrical connection with the SRA system, which will be described in detail in next section.

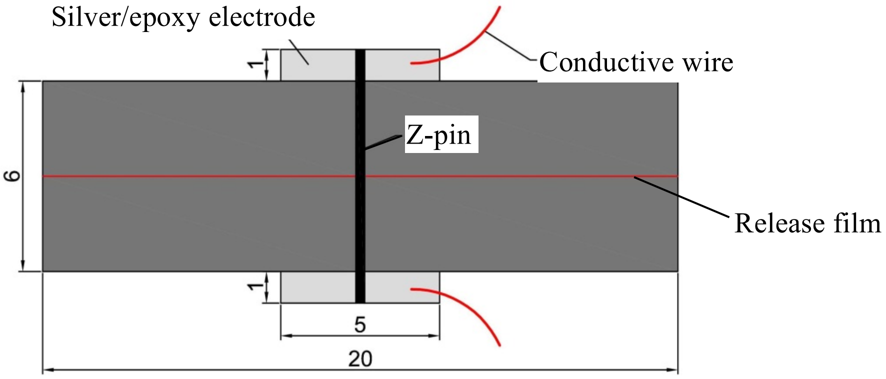


Figure 1: Sample configuration for sensing Z-pin bridging test.

The coupon manufacture procedure was the same as the one described in Ref. [4], except for the Z-pin insertion and the electrode arrangement. Regarding the insertion, the Z-pin was left with 1mm long segments protruding from both sides of the laminate, rather than the excess length being sheared off as in Ref. [4]. The electrodes were bonded to the sample after the curing of the Z-pinned laminate. In order to manufacture the electrodes, the laminate surfaces and the protruding Z-pin ends were cleaned by acetone. Special care was placed on avoiding any damage to the protruding ends. Silver loaded epoxy adhesives (1:1 mixing ratio) were brushed around the protruding Z-pin ends, with the assistance of a removable mould, as shown in Fig. 2. The mould has a hollow central slot (5mm × 5mm area and 1mm thick) to accommodate and shape the brushed adhesive. In addition, the mould also has a side slot which holds the wire connected to the electrode. Finally, the whole sample was placed into an oven for curing at 80°C for 15 minutes in order to cure the electrodes, and then cooled down gradually. The final sample configuration is shown in Fig. 1.

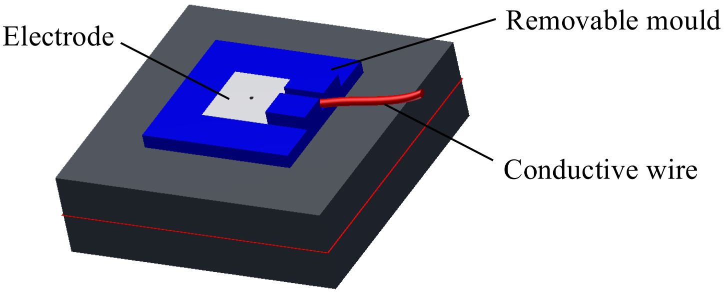


Figure 2: Electrode manufacture with the assistance of a removable mould.

3 EXPERIMENT SET-UP

3.1 Mechanical loading set-up

Bridging loads were exerted on the single Z-pin coupons using a calibrated Instron 8872 hydraulic test machine with a 1KN load cell, at a loading rate of 0.5mm/min. Different fixtures were used for the Mode I and Mode II tests. The Mode I load was transferred via two steel tabs. Two spacers were inserted between the coupon and the tabs. The spacers were used to protect the protruding Z-pin ends, the electrodes and the conductive wires, but also to electrically insulate the coupon from the conductive tabs. Hence, the spacers were non-conductive, and possessed high stiffness and strength in order to reduce the compliance of the loading system. In this study, 20mm × 4mm E-glass/913 laminate strips with thickness of 2mm were selected as the spacers. The spacers were bonded to the coupon and the tabs using cyanoacrylate superglue (Loctite Corp., UK). Special care was taken to ensure that the glue is not applied onto the electrodes. An initial compression loading of -20N was applied on the sample for 15minutes in order to ensure complete curing of the cyanoacrylate adhesive.

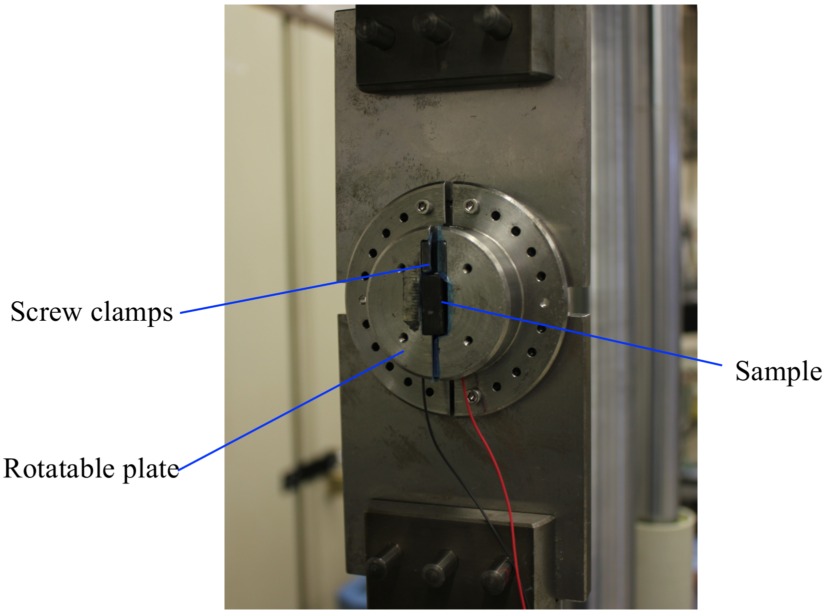


Figure 3: Loading set-up for Mode II bridging case.

Fig. 3 presents the Mode II fixture used to transfer shear loading to the single Z-pin specimens. The fixture is a modified Arcan jig [4]. The jig comprises a central rotating plate, which is split in half. The plate can be rotated in order to obtain various mode mixities. The plate has a central slot to accommodate the coupon. The specimen was attached to the top and bottom halves of the plate using two screw clamps. This approach allows inserting electrically insulating media between the sample and the conductive jig. The inserted insulating medium was electrical PVC tape. The jig half plates comprise two radius slots. The slots were designed in order to accommodate the protruding Z-pins and electrodes, and for connecting the conductive wires to the SRA system.

3.2 SRA system

As shown in Fig. 4, the sensor reading and analysis (SRA) system consists of a Keithley 7703 multiplexer as channel selection unit, a Keithley 2700 digital multimeter as measurement unit, communication modules and a PC running the NI LabVIEW program for the control of the whole SRA system and TTER data acquisition. The communication modules comprise an RS232-USB cable for the data transmission between the multimeter and the PC, and a PCI-9114 data acquisition card (DAQ) for the data transmission between the machine and the PC. The Keithley 2700 is a high-performance digital multimeter with the maximum measurement resolution of 6.5 digitals [11]. It has a built-in switch mainframe that can implement channel-scanning operation locally or remotely in combination with plug-in Keithley 77XX series switch modules. In this study a Keithley 7703 multiplexer was used as the switch module. The multiplexer can allow 32 channels of 2-wire ER measurement or 16 channels of 4-wire ER measurement. Since this study is focused on single Z-pin tests, one of the 2-wire measurement channels was selected for the TTER measurement. However, this SRA system can be directly used for multiple channel measurement in the Z-pin reinforced laminates. The TTER measurement resolution and data acquisition rate were respectively set to 6.5 digits and 20 readings/s for the single Z-pin test.

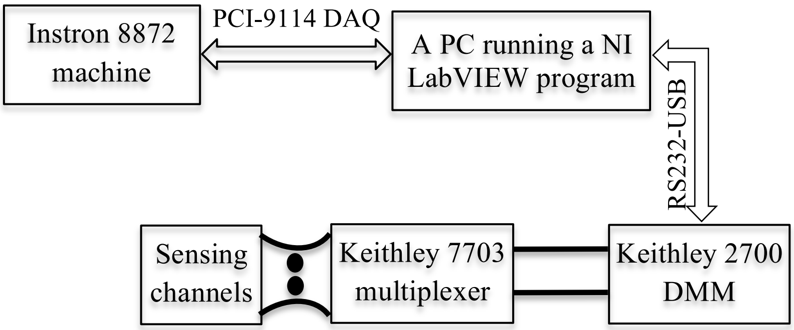
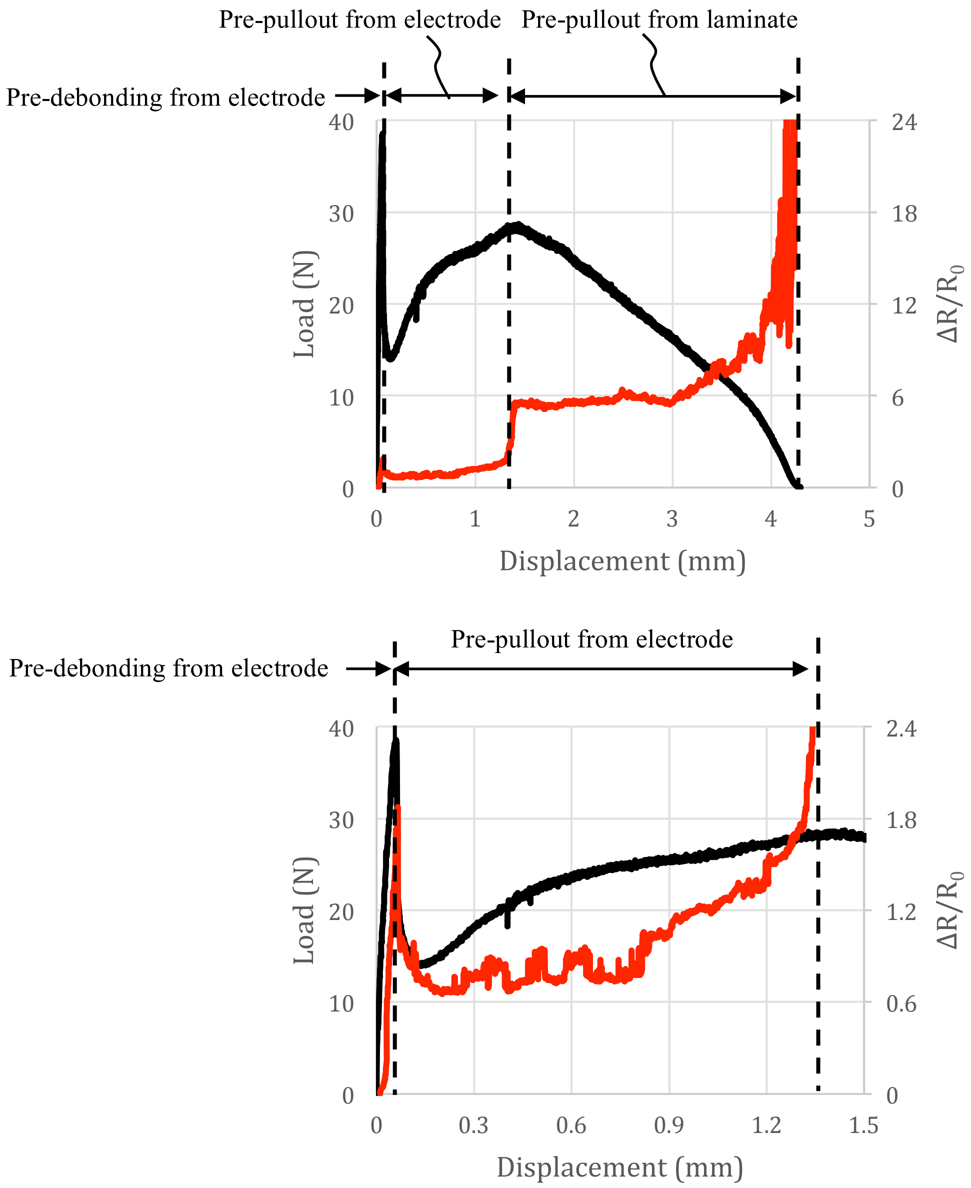


Figure 4: The SRA system used for ER signal measurement and acquisition.

4 RESULTS

3.1 Mode I

The typical Mode I result is shown in Fig. 5a. The whole Z-pin pullout process can be divided into three stages: pre-debonding from one side of electrode, pre-pullout from the debonded electrode and pre-pullout from laminate. For clarity, the experimental force-displacement and TTER-displacement responses associated with first two stages are enlarged in Fig. 5b. At the pre-debonding-from-electrode stage, the bridging force first increases linearly with the elastic elongation of the Z-pin, due to the bonding between the Z-pin and the two electrodes. The Z-pin deformation is accompanied by the gradual failure of the two Z-pin/electrode interfaces. The bridging force arrives at its peak when the majority of the bonding area on the interface with lower bonding toughness has failed. Consequently, the bridging force will drop dramatically with sudden contraction of the Z-pin, caused by the fast failure of the remaining bonding area of the lower-toughness interface. Regarding the TTER signal at this stage, it also increases with the Z-pin elongation and decreases suddenly with the Z-pin shortening. In other words, the TTER measurement can be used to monitor the Z-pin bridging condition at this stage. In addition, simple calculations show that the sensing gauge factor, i.e., the ratio of the TTER fraction change to Z-pin strain, are much larger than that due to the Z-pin deformation alone. This is attributed to the increase of contact ER existing between the Z-pin and two electrodes, which is the dominant factor contributing to the TTER in the pre-debonding-from-electrode stage.



(b)

Figure 5: (a) Full-range plots and (b) partially enlarged plots of typical Mode I results.

At the beginning of the pre-pullout-from-electrode stage, shown in Fig. 5b, the bridging load is immediately picked up by the friction exerted on the whole length of the Z-pin. Furthermore, the bridging force shows an increasing trend, reaching its peak at the moment when the protruding Z-pin segments completely slide into the laminate. The friction at this stage is due to both the Z-pin/electrode and the Z-pin/laminate interfaces. As discussed in [2], in single Z-pin pullout Coulomb friction dominates near the fracture plane, while residual friction plays a major role far from the delamination. Coulomb friction is present because Z-pins always exhibit a misalignment angle with respect to the nominal orthogonal insertion direction. However, for the Z-pin configuration considered here, the effect of the protruding ends being dragged into the laminate is also significant in determining the actual pullout behaviour. The TTER signal in this stage is affected by noise due to the instable contact ER between the Z-pin and the electrodes. However, given the clear trend in bridging force and TTER, it can be concluded that the TTER signal can be used to monitor the Z-pin bridging regime in the pre-pullout-from-electrode stage.

Once the protruding Z-pin ends completely slide into the laminate the pre-pullout-from-laminate stage starts. The TTER value exhibits a sudden increase. Afterwards, the ER signal presents an overall increasing trend, albeit affected by noise. On the other hand, the bridging load exhibits a gradually decreasing trend at this stage, until complete pin pullout. Once the Z-pin is completely pulled out, the TTER value becomes infinite. Overall, the Z-pin bridging condition during the whole pullout process in Mode I can be monitored by measuring the TTER.

3.2 Mode II

The behaviour of a single Z-pin subject to Mode II deformation is drastically different from that occurring in Mode I. As shown in Fig. 6, the bridging force increases monotonically with the Z-pin deformation, until a catastrophic pin rupture occurs. Regarding the mode II delamination-sensing ability, the TTER signal shows no clear trend up to a sliding displacement that is in the order of half the Z-pin diameter. Two mechanisms are responsible for this behaviour: upon delamination sliding, the Z-pin experiences an increasing lateral pressure and this causes an increase in conductivity due to percolation. However the sliding also causes an axial stretching of the Z-pin, which increases the TTER resistance. This effect tends to become dominant as the lateral sliding increases. At sliding displacements approaching half the Z-pin diameter, the TTER has a sharp increase due to the progressive fibre failure that occurs in the Z-pin close to the delamination plane. The TTER become infinite when the Z-pin is fully failed. This behaviour suggests that there exists a “blind” region, where it is not possible to detect the Z-pin deformation and the presence of delamination since the effect on the TTER is too small and the associated trend not clear. However, when the Z-pin is approaching failure, the change of TTER is large enough to allow detecting the presence of delamination.

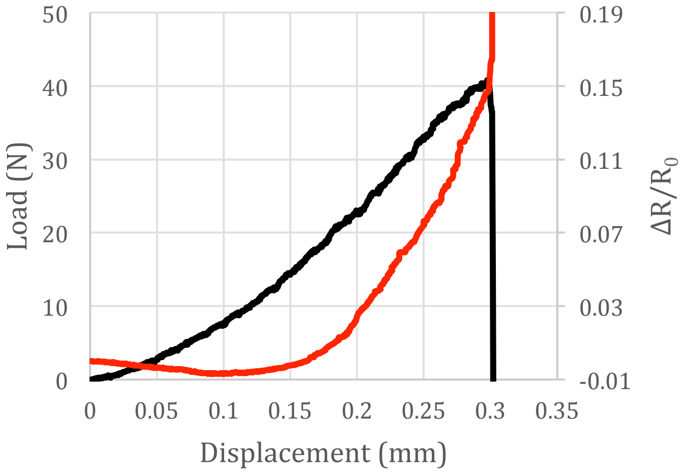


Figure 6: Plots of typical Mode II results.

5 CONCLUSIONS

This paper provides an assessment of the through-thickness sensing function of Z-pin reinforced composites laminates. The through-thickness electrical resistance (TTER) was measured and correlated to the progressive pullout/failure of Z-pin in Mode I and Mode II. The electrical connection between the Z-pin and a sensor reading and analysis (SRA) system was achieved via electrodes that are bonded to the Z-pin ends protruding from both sides of a through-thickness reinforced laminate. The SRA system comprises a multiplexer as sensing channel selection unit, a digital multimeter as ER measurement unit, communication modules and a PC that runs a NI LabVIEW program for the control of the whole SRA system and ER data acquisition. The sensing behaviour was characterised by mechanical tests performed on 6mm thick laminates comprising single T300/BMI Z-pins. Results show that the whole pull-out process for a Z-pin loaded in Mode I can be monitored by the TTER signal. The Z-pin deformation under Mode II bridging can also be monitored by the TTER detection, albeit there exists an initial “blind-spot” at relatively small lateral deformation. However, the Z-pin rupture in Mode II loading can be clearly detected as an abrupt TTER increase.

This study demonstrates that through-thickness reinforcement elements as Z-pins can also be employed as sensors for the reinforced laminates. This paves the way to the development of multi-functional through-thickness reinforcement.

ACKNOWLEDGEMENTS

The authors would like to acknowledge Rolls-Royce for the support of this research through the Composites University Technology Centre (UTC) at the University of Bristol, UK.

REFERENCES

[1] Partridge IK, Cartié DDR. Delamination resistant laminates by Z-Fiber® pinning: Part I manufacture and fracture performance. Compos Part A Appl Sci Manuf 2005;36:55–64.
[2] Zhang B, Allegri G, Hallett SR. High-fidelity modelling of Z-pins in quasi-istropic laminates. 16th Eur. Conf. Compos. Mater., Seville, Sapin: 2014.
[3] Allegri G, Yasaee M, Partridge IK, Hallett SR. A novel model of delamination bridging via Z-pins in composite laminates. Int J Solids Struct 2014;51:3314–32.
[4] Yasaee M, Lander JK, Allegri G, Hallett SR. Experimental characterisation of mixed mode traction–displacement relationships for a single carbon composite Z-pin. Compos Sci Technol 2014;94:123–31.
[5] Cox BN. Snubbing effects in the pullout of a fibrous rod from a laminate. Mech Adv Mater Struct 2005;12:85–98.
[6] Cartié DDR, Troulis M, Partridge IK. Delamination of Z-pinned carbon fibre reinforced laminates. Compos Sci Technol 2006;66:855–61.
[7] Rugg KL, Cox BN, Massabo R. Mixed mode delamination of polymer composite laminates reinforced through the thickness by z-fibers 2002;33:177–90.
[8] Bianchi F, Koh TM, Zhang X, Partridge IK, Mouritz a. P. Finite element modelling of z-pinned composite T-joints. Compos Sci Technol 2012;73:48–56.
[9] Angelidis N, Wei CY, Irving PE. The electrical resistance response of continuous carbon fibre composite laminates to mechanical strain. Compos Part A Appl Sci Manuf 2004;35:1135–47.
[10] Wang S, Chung DDL, Chung JH. Impact damage of carbon fiber polymer–matrix composites, studied by electrical resistance measurement. Compos Part A Appl Sci Manuf 2005;36:1707–15.
[11] https://www.keithley.co.uk. Model 7703 32-Ch, High-Speed, Diff Mux Module 2014.