Composites Science and Technology 128 (2016) 138–146

Contents lists available at ScienceDirect

Composites Science and Technology

journal homepage: http://www.elsevier.com/locate/compscitech

On the delamination self-sensing function of Z-pinned composite laminates

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ARTICLE INFO

Article history:
Received 21 October 2015
Received in revised form
17 March 2016
Accepted 18 March 2016
Available online 19 March 2016

Keywords:
Structural composites
Smart materials
Delamination
Z-pinning

ABSTRACT

This paper investigates for the first time the usage of through-thickness reinforcement for delamination detection in self-sensing composite laminates. Electrically conductive T300/BMI Z-pins are considered in this study. The through-thickness electrical resistance is measured as the delamination self-sensing variable, both for conductive and non-conductive laminates. The Z-pin ends are connected to a resistance measurement circuit via electrodes arranged on the surface of the laminate. The delamination self-sensing function enabled by conductive Z-pins is characterised for Mode I/II delamination bridging, using single Z-pin coupons. Experiment results show that, if the through-thickness reinforced laminate is electrically conductive, the whole Z-pin pull-out process associated with delamination bridging can be monitored. However, for a non-conductive laminate, delamination bridging may not be sensed after the Z-pin is pulled out from one of the surface electrodes. Regardless of the electrical properties of the reinforced laminate, the through-thickness electrical resistance is capable of detecting Mode II bridging, albeit there exists an initial "blind spot" at relatively small lateral deformation. However, the Z-pin rupture can be clearly detected as an abrupt resistance increase. This study paves the way for exploring multi-functional applications of through-thickness reinforcement.

1. Introduction

Multi-functional composites have attracted an increasing research interest over the past two decades. Multi-functionality usually involves a load-bearing capability coupled with strain/temperature/damage sensing, structural actuation and energy harvesting [1]. Multi-functional composites can be mainly classified into two: 1) additional-phase activated composites; 2) self-functioning composites. Typical examples of the former are carbon nanotube-filled composites, which offer both sensing and actuation functionalities [2,3]. On the other hand, a carbon-fibre reinforced polymer (CFRP) can be regarded as a self-functioning composite, as it offers an inherent delamination detection function through electrical resistance (ER) or electric potential measurements [4–6], without the need of embedding additional "smart" phases in the baseline material.

Traditional polymer-based composite laminates possess excellent in-plane performance, but they are prone to suffer delamination between plies, particularly when subjected to impact. Thus several through-thickness reinforcement (TTR) technologies such as stitching, 3D weaving and tufting have been developed to improve interlaminar strength and toughness of composite laminates [7]. Z-pinning is an effective TTR technology, whereby small diameter rods (Z-pins) are inserted through the thickness of laminates [8]. The mechanical performance of Z-pinned composites has been assessed in several experimental [9,10] and modelling studies [11–13]. However, regarding multi-functionality, only a single conceptual study on the sensing performance of TTR laminates comprising piezoelectric Z-pins is available in the literature [14].

The most commonly used Z-pins consist of small-scale (less than 1 mm diameter) CFRP rods, made of carbon-fibres consolidated into BMI matrix. In this study we consider 0.28 mm diameter Z-pins, which have 1k filament count tows and 63% nominal fibre-volume-fraction. Small-scale CFRP rods can self-sense strain via measurements of longitudinal ER [15]. This implies that, at least in principle, self-sensing functions may be enabled in TTR laminates by the presence of Z-pins.

This paper for the first time validates the usage of TTR for delamination detection in self-sensing composite laminates. The

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http://dx.doi.org/10.1016/j.compscitech.2016.03.019
0266-3538/

strain sensing capability provided by individual T300/BMI Z-pins under pure tension is considered first, via measurements of the longitudinal ER. Then, delamination sensing via through-thickness electrical resistance (TTER) measurements is investigated in carbon/epoxy (CFRP) and glass/epoxy (GFRP) single Z-pin coupons, under Mode I and Mode II regimes.

2. Specimen preparation

Fig. 1 shows the configuration of single Z-pin tension coupons, which had a 20 mm gauge length. Tensile loading was applied via two GFRP tabs, which were bonded to the pin using AS89.1/AW89.1 adhesive (Cristex Ltd, UK). The bonding length was 25 mm on each side. The tabs were aligned to the Z-pin using a paper card [16]. Two outer electrodes and two inner electrodes were bonded to the Z-pin ends, for current injection and voltage measurement respectively. Thus a 4-wire ER measurement set-up was employed in order to factor out the effect of Z-pin/electrode contact ER. Silver/epoxy conductive adhesives (1:1 wt ratio) were used for manufacturing the electrodes. These were cured at 80 °C for 15 min in an oven. The electrodes were positioned outside of the gauge length, in order to avoid damaging the Z-pin/electrode interfaces while applying loading. Each electrode was also bonded to a conductive wire.

As shown in Fig. 2a, the coupon configuration for single Z-pin bridging tests is analogous to that considered in Ref. [9], although some modifications were introduced in order to accommodate the electrodes. The coupon consisted of a prismatic laminate block, which was split into two halves on the mid-plane by a PTFE release film. The laminate was made of 48 plies of unidirectional prepreg, with stacking sequence $[(-45/90/45/0)_s]_6$. Two different prepreg materials were employed, namely: conductive carbon/epoxy IM7/8552; and non-conductive glass/epoxy E-glass/913 (Hexcel, UK). The average coupon thickness was 6.0 mm for CFRP and 6.8 mm for GFRP. A single Z-pin was inserted through the thickness of the laminate, with 1 mm long tips protruding from both the top and bottom surfaces of the laminate. Two prismatic electrodes with 5×5 mm^2 in-plane dimensions were bonded to the protruding Z-pin ends. The electrodes were made of the same material employed for the tension coupons. Thus, a 2-wire ER measurement method was used in the bridging test. For sake of clarity, a CFRP TTR rod connected to the electrodes is called a “sensing” Z-pin; otherwise, we shall refer to the TTR rod as a “mechanical” Z-pin.

Due to the electrode arrangement, the “sensing” Z-pin bridging coupon requires a different manufacture process in comparison with the “mechanical” Z-pin specimen described in Ref. [9]. Specifically, 1 mm thick rubber sheets were first placed on the bottom and top surfaces of the laminates. The Z-pins were inserted through the entire thickness of the laminate/rubber-sheet assembly, as shown in Fig. 2b. The Z-pin ends were then sheared off on the rubber sheets. The plate was then cured in an autoclave following the manufacturer's recommendations (2 h at 180 °C with 100 psi pressure for CFRP, and 1 h at 125 °C and 100 psi for GFRP). The rubber sheets were peeled off after cure, leaving 1 mm long Z-pin ends protruding on the laminate surfaces, as already mentioned above. Next, the plate was carefully cut into individual coupons, as shown in Fig. 2c. After the coupon surfaces were cleaned by acetone, the electrodes were positioned with the aid of removable moulds, as shown in Fig. 2d. Each mould had a central hollow slot to accommodate and shape the electrode, as well as a side slot to hold the wire in position. The Z-pin ends were fully embedded within the electrodes.

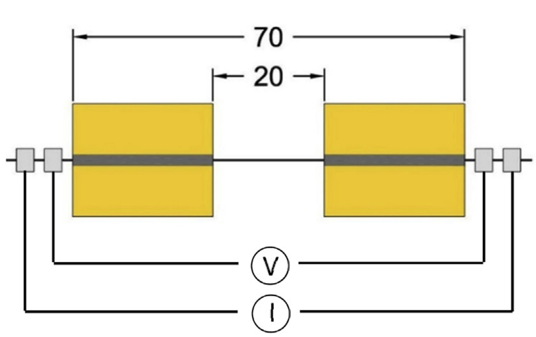

Fig. 1. Configuration of single Z-pin coupon for tension test (mm).

3. Experimental set-up

All the tests were carried out via a calibrated Instron 8872 servo-hydraulic machine, equipped with a 1 kN load cell. For the tension tests, the coupons were gripped at the end tabs, as shown in Fig. 3. The tensile load was applied at the rate of 0.1 mm/min. The paper card attached to the specimen for alignment was carefully cut into two halves along its central line prior to testing, as indicated in Fig. 3. As shown in Fig. 4a, Mode I loading was applied to the bridging coupons via two steel tabs. Two spacers were inserted between the specimen and each of the tabs, in order to protect the electrodes that embed the Z-pin ends. The spacers must be electrically insulating and high-stiffness, in order to eliminate any spurious effect on the TTER and reduce the overall loading-system compliance, respectively. In this study, each spacer consisted of a $20 \times 4 \times 3$ mm^3 (length × width × thickness) E-glass/913 laminate block. The spacers were bonded to the coupon and the tabs using cyanoacrylate superglue (Loctite Corp., UK). Fig. 4b shows that Mode II loading was applied to the bridging specimens via a modified Arcan rig, as in Ref. [9]. The central plate of the rig can be rotated to obtain various mode mixities, albeit only a 90° orientation (Mode II) was used in this study. The plate comprises a central slot to accommodate the specimen. The testing coupon was attached to the top and bottom halves of the plate using two screw clamps. These also allowed inserting electrically insulating PVC tape between the coupon and the jig. As shown in Fig. 4c, each half of the plate also comprised a radially oriented slot, which was designed to contain the electrodes and wires. The ER signal was measured by a Keithley 2700 digital multimeter with resolution and sample rate of 6.5 digits and 20 readings/s, respectively. Bridging loading were applied at a displacement rate of 0.5 mm/min.

4. Results and discussions

4.1. Tension tests

Fig. 5a-b present the results of three tension specimens. All the coupons showed a consistent mechanical response. The stress increases linearly with the tensile strain until catastrophic Z-pin failure; all the Z-pins failed in the gauge region. The failure strength and strain are 2021 MPa and 1.5%, respectively. ASTM D3039 tests on unidirectional T300-12k carbon epoxy give a tensile strength of 1860 MPa [12]. The stressed volume for ASTM D3039 coupons is 2250 mm^3, while it is only 1.23 mm^3 for the tensile specimens considered here. Assuming a Weibull modulus of 27 [12], Weibull's strength theory suggests a failure stress of 2456 MPa for 0.28 mm Z-pins. The former value is 20% higher than that obtained experimentally, but this is reasonable considering the difference of filament count and resin system with respect to the material characterised in Ref. [12]. The strength value obtained here also agrees well with that recently reported in Ref. [17] for 0.28 mm T300/BMI Z-pins. However, Cartié et al. [10] reported a strength