INVESTIGATION OF THE DELAMINATION CHARACTERISTICS OF COMPOSITE SPECIMENS WITH THROUGH THICKNESS REINFORCEMENT USING AN INERTIA CONSTRAINED SOFT BODY BEAM BEND TEST SPECIMEN

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Abstract

This paper presents the results from a test programme using a novel test specimen to investigate the delamination of carbon fibre composite specimens under soft body impact loading. The first section introduces the soft body beam bend (SBBB) specimen, whilst the second section presents the results from a test programme which used the SBBB specimen to investigate the effect of through thickness reinforcement (TTR). It is shown that the SBBB specimen is effective at producing a loading state that is representative of what a real component would experience under soft body impact loading. Further to this, the SBBB specimen shows that TTR, in this case z-pinning, is effective at controlling delamination under this loading regime. The level of specimen delamination and the z-pin failure modes have been investigated using ultrasonic c-scanning, high-speed digital photography and scanning electron microscopy and the results from this are presented and discussed.

1. Introduction

Soft body impact loading is one of the critical load cases to consider when designing aerospace structures such as gas turbine engine aerofoils, nose cones or aircraft wing skins. Examples of soft body loading that have to be considered during component design include birdstrike and ice impact. Control of delamination is one of the key challenges when designing laminated composite structures to withstand such loading. So far literature investigating the effectiveness of TTR to suppress delamination during impact has focused solely on low velocity, hard body drop tower impacts [1-6]. Soft body impacts are characterised by high rate loading with more global deflections which cannot be achieved using standard laboratory drop tower equipment.

It is desirable to investigate the effect of TTR during soft body impact loading at a sub-component rather than full-component scale since this allows more parameters to be investigated, reduces the cost, complexity and lead-time of testing and provides more idealised loading conditions which are useful in a multi-scale experimental/modelling development programme. The inertia constrained soft body beam bend (SBBB) test specimen described in this paper provides a method for investigating soft body impact loading at a sub-component level and modification of the specimen has allowed the investigation of the effect of TTR under such loading.

2. SBBB test method

The SBBB test method was first described in the Rolls-Royce owned patent US7845207 (B2). The test method was developed as a solution to the following requirements: the test shall be cost effective and low cost to carry out compared to component testing, unrepresentative damage at the impact site and constraints should be avoided, the constraints should be easy to replicate in finite element models and the loading must be representative of soft body impact loading on a real component. Representative loading is defined as an impact velocity in the region of 100-200m/s, creating through thickness shear loading either side of the impact site in combination with, and followed by, high in-plane bending stresses and a fully reversed bending response.

Figure 2.1 shows a schematic of the SBBB test method and a photograph of the test setup installed at Cranfield University's Shrivenham Campus. The SBBB test method is a tuned dynamic system, and variables such as span, thickness, height, profile and mass of restraints can be modified to get the desired response. Inertial restraints were used in order to avoid unrepresentative failures at the restraints that are common with rigidly clamped boundaries. Furthermore, rigidly clamped boundaries are difficult to recreate in finite element models due to the difficulty in achieving the non-slip condition (as modelled) in the actual test [7]. The inertial restraints have a large length/diameter aspect ratio in order to maximise their weight while ensuring a low rotational inertia therefore reducing any specimen bending stresses at the restraints. The specimen is clamped into the inertial restraints to a torque of 16Nm to ensure that they do not pull-out or slip during testing whilst avoiding localised crushing. The length of the clamped region is 15mm at either end of the specimen. Long wires are used to suspend the inertial restraints which results in a period of oscillation which is many times greater than the specimen itself, thus ensuring that multiple load reversal cycles are achieved in the specimen before it swings out of view of the high-speed cameras.

A gelatine projectile is fired out of a gas gun at velocities ranging from approximately 100-200m/s, which is representative of an aircraft forward speed during take-off/climb or the normal velocity between a soft body and a rotating aerofoil of a gas turbine engine.

A high speed camera positioned orthogonal to the specimen is used in order to track projectile velocity, determine specimen deflection time-histories (using motion tracking techniques) and to observe failure sequences. A general view high speed camera is also used to check the impactor strike location and observe if any secondary damage occurred on the specimen after it had moved out of view of the orthogonal camera. The top edge of each specimen was painted white to aid visualisation of delaminations on the high speed videos.

The manufacture of the test fixtures and the development of the gelatine firing method, in addition to the testing itself was carried out by the Defence Academy of the United Kingdom, Cranfield University in Shrivenham.

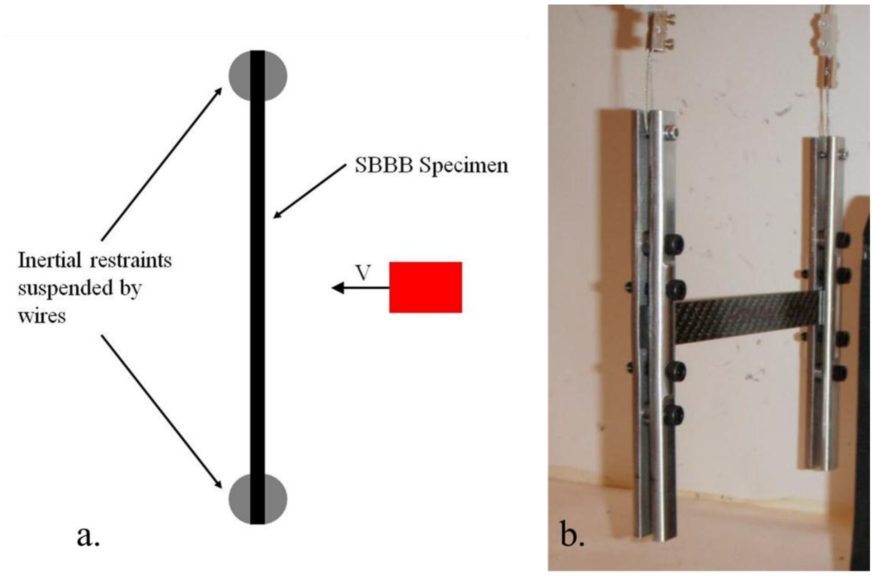

Figure 2.1. a. Schematic of SBBB test setup, b. SBBB test setup installed at Cranfield University, showing showing inertial restraints attached to c.1m long suspending wires

3. Modification of SBBB specimen to allow investigation of TTR

The SBBB specimen was modified in order to investigate the effectiveness of TTR in the suppression of delamination caused by soft body impact loading. Z-Pinning was the method of TTR applied to all specimens. Z-Pinning involves inserting carbon fibre rods through the thickness of a preform prior to moulding in order to provide fibre reinforcement through the thickness of a laminate. All z-pins were supplied by Albany Engineered Composites and were 0.28mm diameter, 2% areal density T300/bismaleimide rods. Z-Pinning was chosen as the method of TTR since it has been shown in numerous studies to significantly increase the delamination resistance of pre-impregnated composite structures [8,9]. In addition to this, z-pinning has already been proven on industrial applications such as the F/A-18 Superhornet and the F-35 Lightning II aircraft [10,11].

Figure 3.1 shows a schematic of the z-pinned specimen. The specimens were 200mm long by 20mm wide. The modifications include the insertion of a seeded delamination in combination with z-pin bands either side of the seeded delamination. The seeded delamination consisted of a 20mm wide, 15µm thick PTFE film inserted at the mid-plane of the specimen during layup. The seeded delamination was used to ensure a known initiation location for the delamination, thus ensuring more consistent results. A 20mm gap was left between the edge of the seeded delamination and the z-pins to ensure that the z-pins would be exposed to a sharp running crack. Three different z-pin band widths were tested, which were nominally 10mm, 20mm and 30mm. Each 10mm band featured 7 z-pins across its width, hence the 20mm band was 14 z-pins wide and the 30mm band was 21 z-pins wide.

All specimens were manufactured to a $[0\ 45\ -45\ 90\ 45\ 0\ -45\ 0\ 45\ 90\ -45\ 0]_s$ layup using unidirectional carbon-fibre toughened epoxy pre-impregnated material, with a layer of 2x2 twill carbon-fibre toughened epoxy pre-preg woven material applied to each surface. This specimen configuration resulted in specimens that were approximately 5mm thick.

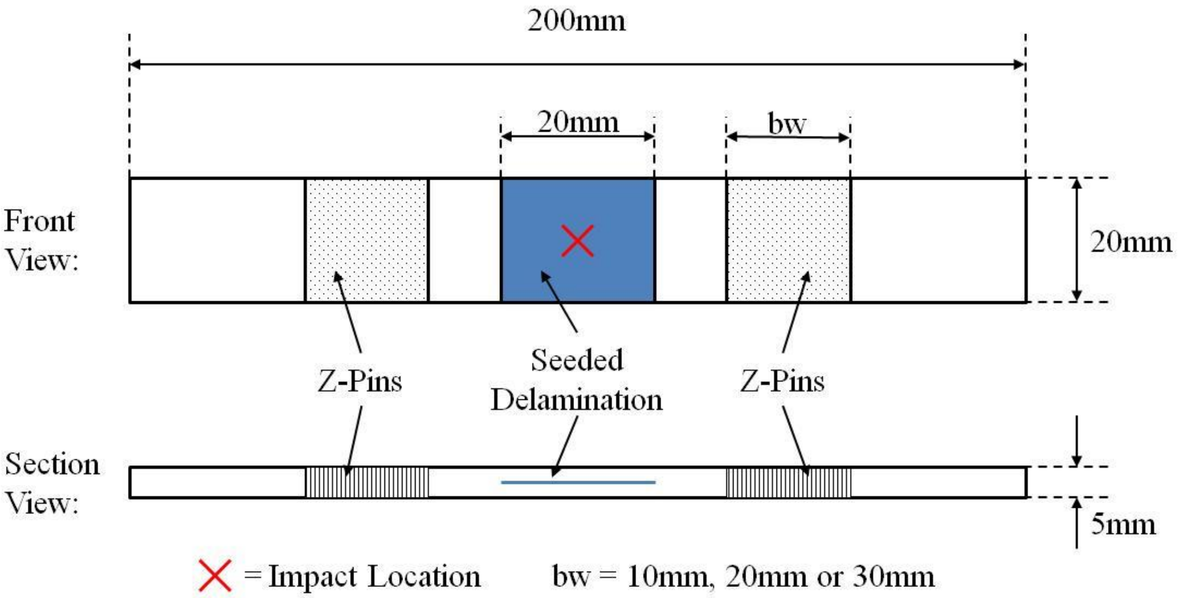

Figure 3.1. Schematic of z-pinned SBBB specimen

4. Test Results

Specimens with and without z-pins were tested at different impact velocities, while impactor mass and position remained constant for all tests. The threshold velocity was used as a measure to compare the performance of different specimen configurations. The threshold velocity (V_T) is defined as the velocity above which the mid-plane delamination propagated all the way to the end constraint.

The inertial restraints behaved as desired during the testing and no failures occurred at the end restraints. Figure 4.1 shows the response of the specimen during/after impact.

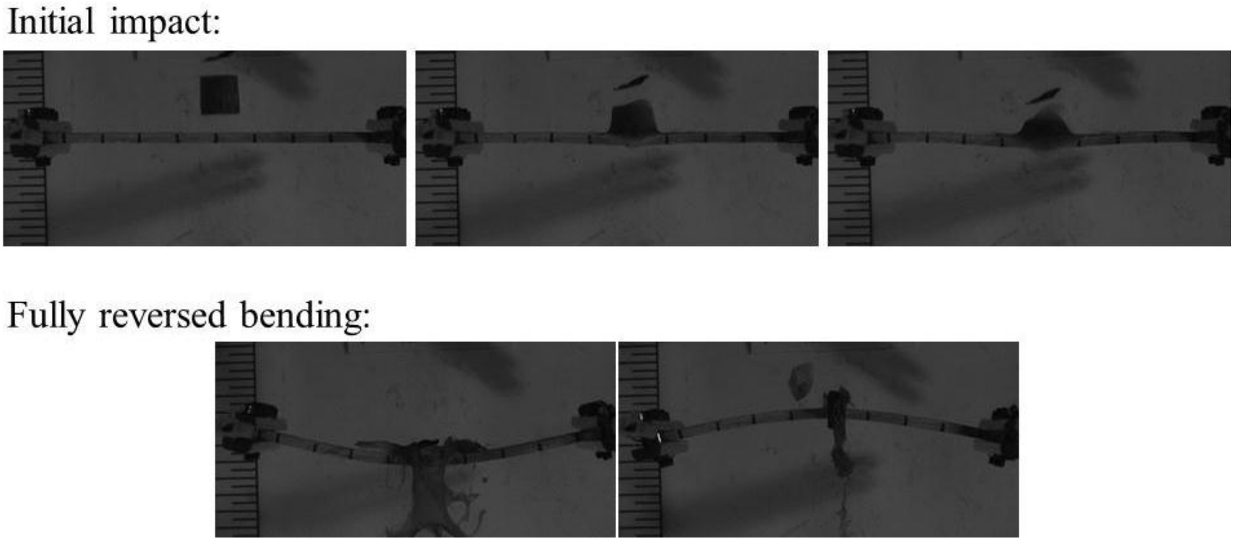

Figure 4.1. Response of specimen during the initial impact and subsequent fully reversed bending

Figure 4.2 shows the relationship between z-pin band width and normalised threshold velocity (V_{TN}) and normalised threshold impact energy (E_{TN}). All specimens were impacted with nominally 20x20mm cylindrical gelatine impactors with a mass of 6.7grams +/-0.3grams.

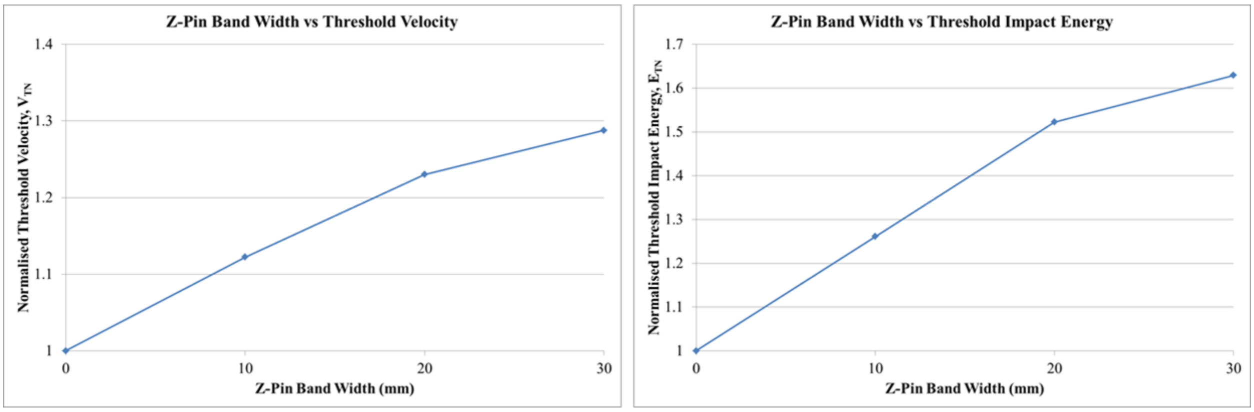

Figure 4.2. Relationship between z-pin band width and normalised threshold velocity/impact energy

Figure 4.3 shows ultrasonic c-scans of unpinned and z-pinned specimens. Delaminations are highlighted by green/turquoise colours, whereas undamaged regions are dark blue. Note that all specimens featured a 20mm wide seeded delamination in the central position which also shows up as a delamination. Above V_{TN}=1 the delamination extended right up to the end fixings in the unpinned specimen, whereas in the z-pinned specimen this did not occur until V_{TN}=1.29. This represents a c.30% increase in threshold velocity which translates to a c.60% increase in threshold impact energy. Z-pinned specimens also showed more gradual progression of delamination extent compared to the unpinned specimens. In one of the z-pinned specimens shown in Figure 4.3 the z-pins were inserted c.10mm out of position. However, results from other specimens provide confidence that this does not significantly affect the result.

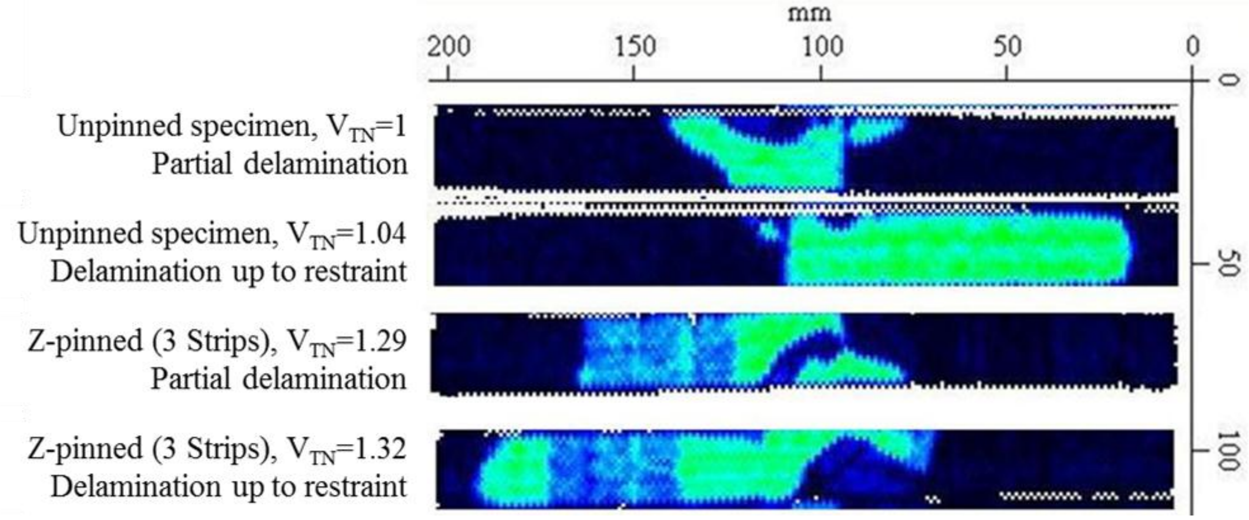

Figure 4.3. SBBB specimen c-scans

5. Discussion

Z-pinning has been shown to increase the threshold impact energy by up to 60% relative to unpinned specimens on a toughened pre-preg epoxy carbon fibre material system. This is broadly consistent with drop tower results published by Isa et al [1] which showed that z-pinned specimens had less delamination than unpinned specimens even when they were impacted with c.30% greater impact energy. However this increase in energy is relatively small when compared to increases in static fracture energies of 25 and 7.5 fold in DCB and ENF specimens respectively which have been previously reported [10, 12]. The improvement shown in the SBBB specimens is of particular interest since the SBBB specimen is predominantly Mode II loaded. The mode of loading in the SBBB specimen was determined by carrying out fractography and LS-Dyna modelling. Figure 5.1 is taken from an LS-Dyna model of the specimen which shows the mixed mode ratio of a mid-plane element close to the edge of the seeded delamination. Mixed mode ratio was calculated by taking the ratio of though thickness shear stress (σ_{13}) divided by direct through thickness stress (σ_{33}). Figure 5.2 is a scanning electon microscopy (SEM) image of a typical SBBB specimen showing shear cusps which confirm the Mode II loading [13]. Previous literature has shown that increases in Mode II fracture toughness due to z-pinning are approximately one third of that for Mode I [10,12] therefore it can be expected that improvements in the delamination threshold of a Mode I dominated component would be even greater.

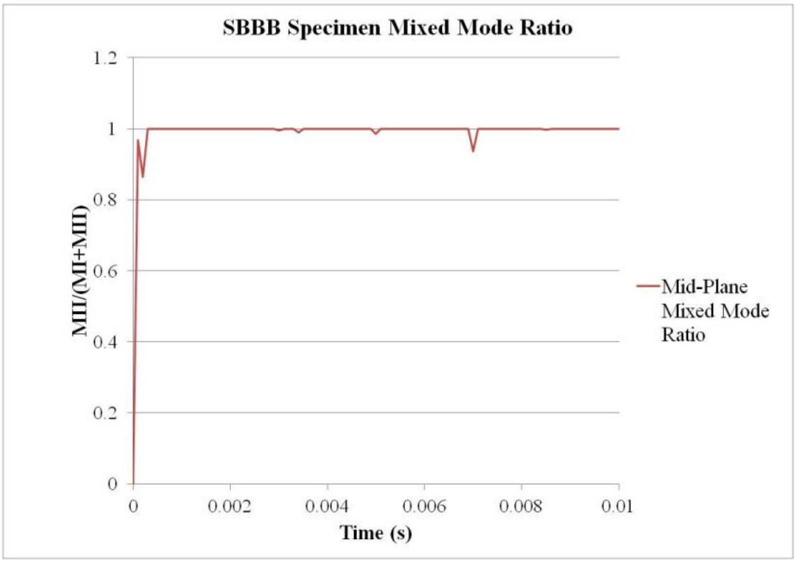

Figure 5.1. Finite element prediction of mixed mode ratio at specimen mid-plane during impact

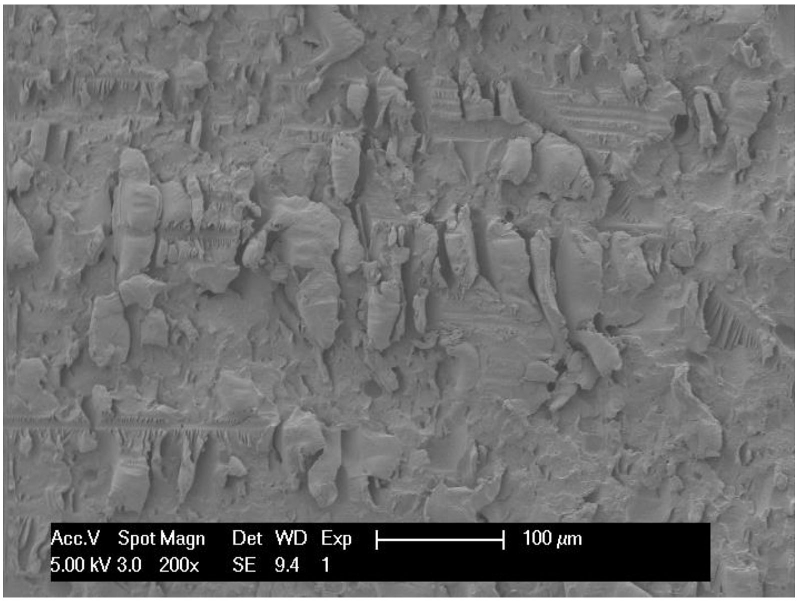

Figure 5.2. SEM image of shear cusps on SBBB specimen

The improvement in delamination resistance shown on the SBBB specimens is due to the energy absorbing mechanisms during failure of the z-pins. Post-test inspection of the specimens and high speed video (see Figure 5.3) showed that the z-pins did not pull-out and hence a review of previous literature [10,13,14] shows that the principal energy absorbing mechanisms are likely to be: elastic shear deformation, lateral deflection of the rod into the substrate (including ploughing of the matrix), internal shear matrix splitting of the pin, flexural failure and transverse shear across the pin thickness. Figure 5.4 shows a SEM image of a typical z-pin failure in a SBBB specimen. The failure shown in Figure 5.4 is consistent with z-pin shear failure due to Mode II loading [13] and clearly shows the ploughing of the pin into the substrate. Failure of the z-pins themselves rather than pull-out is characteristic of Mode II loading since Koh et al [9] showed that a Mode I dominated load stated would be expected to result in pin pull-out with this thickness of specimen.

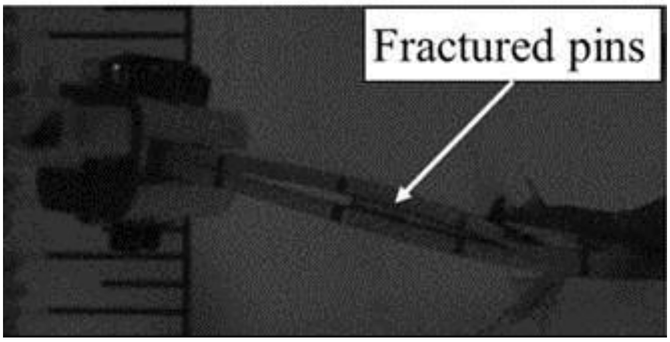

Figure 5.3. Separation of the fracture surfaces during post-delamination response shows that pins have fractured

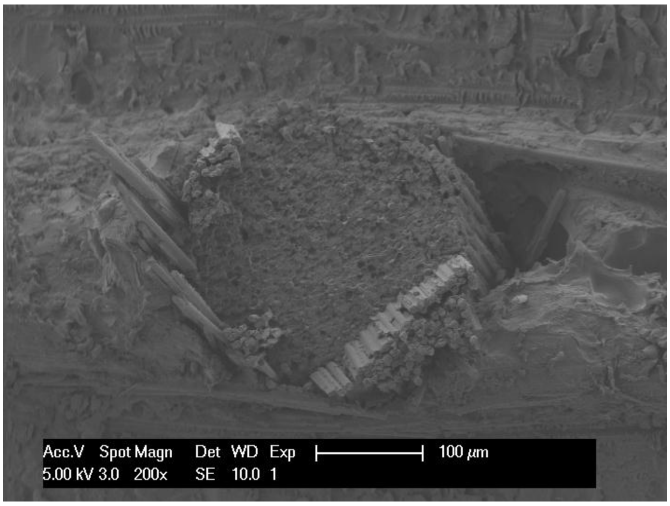

Figure 5.4. SEM image of z-pin shear failure in a SBBB specimen

6. Conclusions

- The SBBB test method has been presented as a simple sub-element specimen that is able to recreate soft body impact load states of real aerospace components.
- The use of inertial restraints were successful in preventing unrepresentative failures at the specimen boundaries.
- The modification of the basic SBBB specimen to include a seeded delamination ensured that the delamination site was controlled thus ensuring consistency between specimens.
- There is potential to extend the SBBB test method to include testing of metallic and sandwich structures as well as tapered cross-sections.

- Z-Pins have been shown to increase the delamination resistance by up to 60% based on impact energy.
- Increases in z-pin band width provide an increase in delamination resistance, with a slight decrease in the rate of increase once the pin band width goes over 20mm.
- The z-pins failed by pin fracture which is consistent with Mode II loading of static structures.

7. Acknowledgements

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