EXPERIMENTAL ASSESSMENT AND DESIGN OF THROUGH THICKNESS REINFORCEMENT IN THICK COMPOSITE LAMINATES SUBJECTED TO BIRD STRIKE LOADING

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Abstract

This paper presents the results of a series of simulated bird strike tests, using gelatine projectiles, which have been carried out on relatively thick, rotating composite components. The purpose of the testing was firstly to identify the failure modes present in the components without any additional through thickness reinforcement (TTR). Components with TTR were then manufactured and tested in order to assess how the global failure modes and extent were affected by TTR. Photographs, CT-scan and C-scan measurements were taken before and after test in order to assess the damage caused by the simulated bird strike. Through thickness reinforcement is shown to be effective at modifying the extent of delaminations within thick composite structures subjected to bird strike loading.

1 Introduction

Aero-engine components have particularly stringent run-on requirements which dictate that an aerofoil must have sufficient integrity after a bird strike in order to run-on for a prescribed time period at a prescribed thrust [1]. In order to meet the certification requirements it is necessary to design a composite aerofoil with sufficient impact tolerance, where impact tolerance is defined as the overall ability to sustain a given impact with a minimum effect on the structure and thus combines both impact resistance and impact damage tolerance [2]. This paper investigates the validity of using through thickness reinforcement (TTR) to control the extent of delaminations with the intention of improving the impact tolerance of a composite aerofoil.

There are several methods of TTR available which have been shown to increase the through thickness strength and fracture toughness of 2D composite laminates including: tufting, stitching, Zanchor, metallic z-pins and carbon z-pins. This paper investigates the use of carbon z-pins as the application method for through thickness reinforcement. Z-pins were chosen due to the fact that they have been shown in several studies to improve the delamination toughness of 2D composite laminates which in turn can increase the impact resistance and damage tolerance of a structure [3]. The improvements in delamination toughness due to z-pinning have been shown to be equal to or greater than other through thickness reinforcement techniques [3]. It has also been demonstrated that z-pins can be successfully applied to aerospace components at an industrial level, for example on the F/A18 Superhornet and the Joint Strike Fighter aircraft [3,4].

This paper describes a series of simulated bird strike tests that were carried out on rotating composite specimens to investigate if it is possible to modify the response of a structure subjected to bird strike through the application of TTR. The requirement to carry out this type of sub-element/component level testing with representative loading has previously been identified by Mouritz [3]. All testing and post-test inspections described in this paper were carried out at the Institut für Leichtbau und Kunststofftechnik (ILK), Dresden for Rolls-Royce plc.

The work presented in this paper is part of a larger project involving the impact testing of composite structures at various scales.

2 Experimental setup

The specimen described in this paper is a composite, aerofoil-like structure. The specimen has chordwise and spanwise taper, but does not feature any twist up the aerofoil. Figure 1 is a photograph of the specimen, giving an indication of the geometry, while Figure 2 shows a photograph of the specimen installed in the spinning rig at the ILK, Dresden. All of the tests were carried out using gelatine to simulate a bird strike.

Figure 1. Photo of specimen

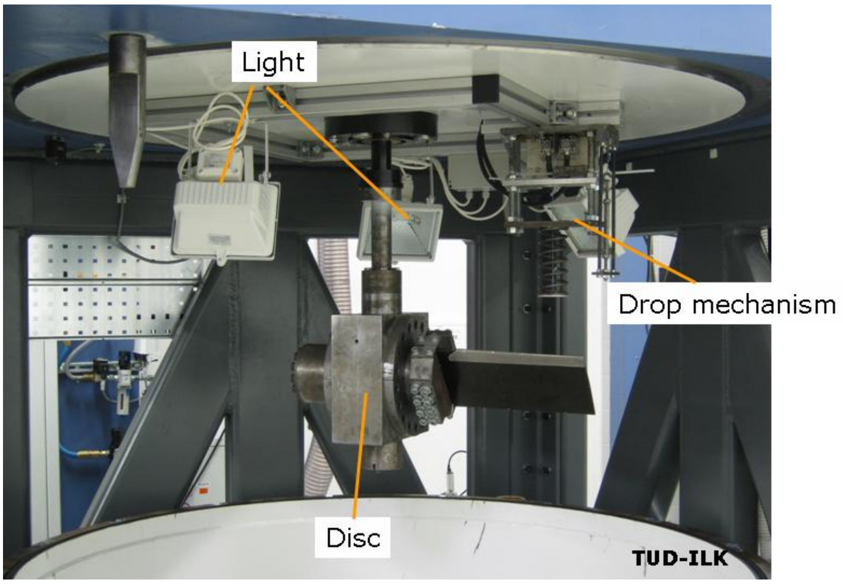

Figure 2. ILK, Dresden spinning rig with a specimen installed

The specimen was designed with simplified geometry relative to a typical modern-day aerofoil. The simplified geometry was employed to allow design iterations to be generated quickly, to allow simpler and quicker post-processing of analysis and test data, and to ensure that high quality and consistent specimens could be manufactured at a reasonable cost.

The following test parameters could be adjusted in order to achieve a variety of impact conditions: rotational speed, specimen incidence angle, gelatine bird size and strike radius. In order to limit the amount of variables it was decided to keep the gelatine bird size and strike radius constant. The specimen incidence angle was kept constant throughout the test programme except for the first test. Any quoted values for impact energy take into account any changes in incidence angle.

Figure 3 shows the region that was reinforced in the z-pinned specimens compared to the unpinned specimens.

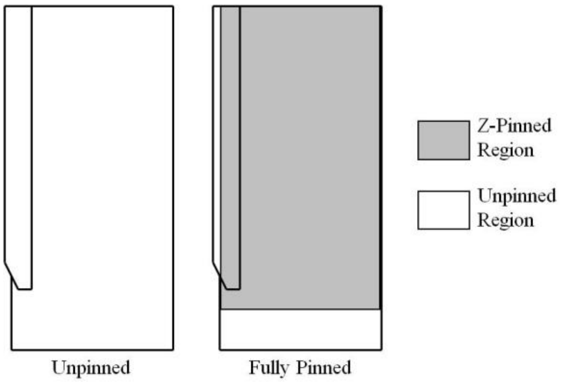

Figure 3. Z-pinned region

The z-pins were designed to pass through the whole thickness of the specimen in all of the z-pinned regions. The reason for pinning through the whole thickness with a single pin was to avoid creating a weak plane without z-pins that could preferentially fail prior to the z-pinned region.

3 Z-pin manufacturing features

The following manufacturing features were identified with the z-pinned specimens, all of which are typical of z-pinned laminates:

- Partial depth z-pin penetration in the thicker regions of the specimen. Typical CT-scans taken at a thick piece of the laminate (c.11mm thick) and a thinner piece of the laminate (c.5mm thick) are shown in Figure 4. It can clearly be seen that some of the pins have not gone through the whole thickness of the laminate in the thick region.
- Non-orthogonal z-pin insertion angle. Figure 4 shows that the axis of the z-pins is not normal to the surface of the specimen. This phenomenon is typical of z-pinned specimens and has been previously reported by Chang et al [5].
- Fibre waviness, resin richness and porosity. Figure 5 contains a CT-scan showing the disruption present as a result of z-pinning. The figure clearly shows how the fibres have had to move in order to accommodate the z-pin. The disruption to the fibres around the z-pins has been shown to result in resin rich zones around the pins [3].

Other manufacturing features that are typical of z-pinning such as fibre crimping, fibre breaking and microcracking due to cure stresses [3] were not investigated in this study.

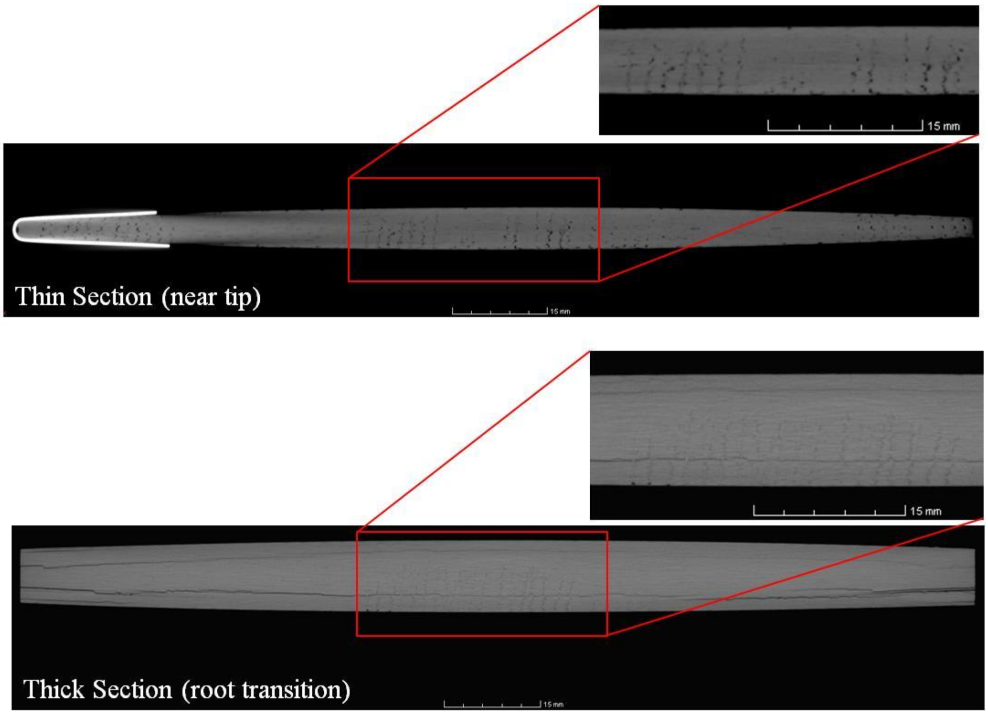

Figure 4. CT-scans of z-pinned specimens

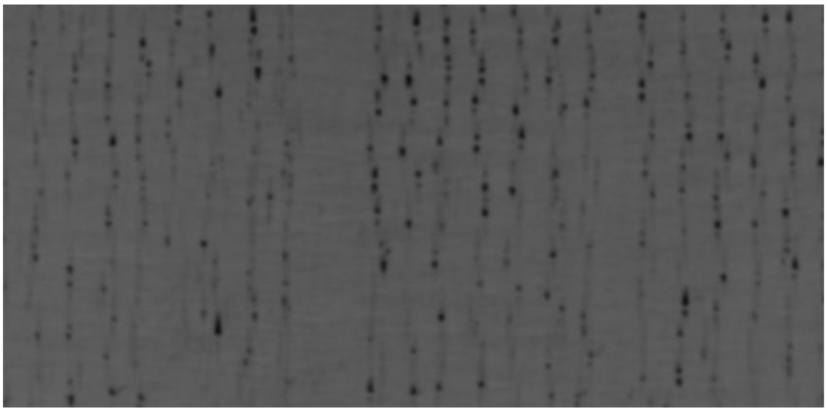

Figure 5. CT-scan showing fibre waviness caused by z-pins

4 Test Results

Figure 6 shows a summary of the c-scan images for the two specimen types plotted against increasing impact energy, where the impact energy was calculated using equation 1. The orientation of the specimens relative to the c-scan is described in Figure 7. The black region featuring in the root region of all specimens is the result of the inability to scan the root region due to its geometry rather than being an indication of delamination. Any test points that fall within the red region of Figure 6 had delamination extents that covered the whole of the aerofoil section of the specimen on one or more planes through the thickness.

$$E = 0.5MV_{RN}^{2} \tag{1}$$

where E = Impact energy, m = Mass of gelatine impacting onto surface

v_{RN}= Resultant velocity of gelatine normal to the surface of the specimen

Figure 8 shows the progression of root damage in each of the two specimen types. There is typically a root delamination, which is not on the mid-plane of the specimen at lower energy levels, whereas at higher energy levels there is a mid-plane delamination which has propagated from the tip of the specimen. The tip delaminations in the fully pinned specimens occurred at higher energy levels compared to the unpinned and partially pinned specimens.

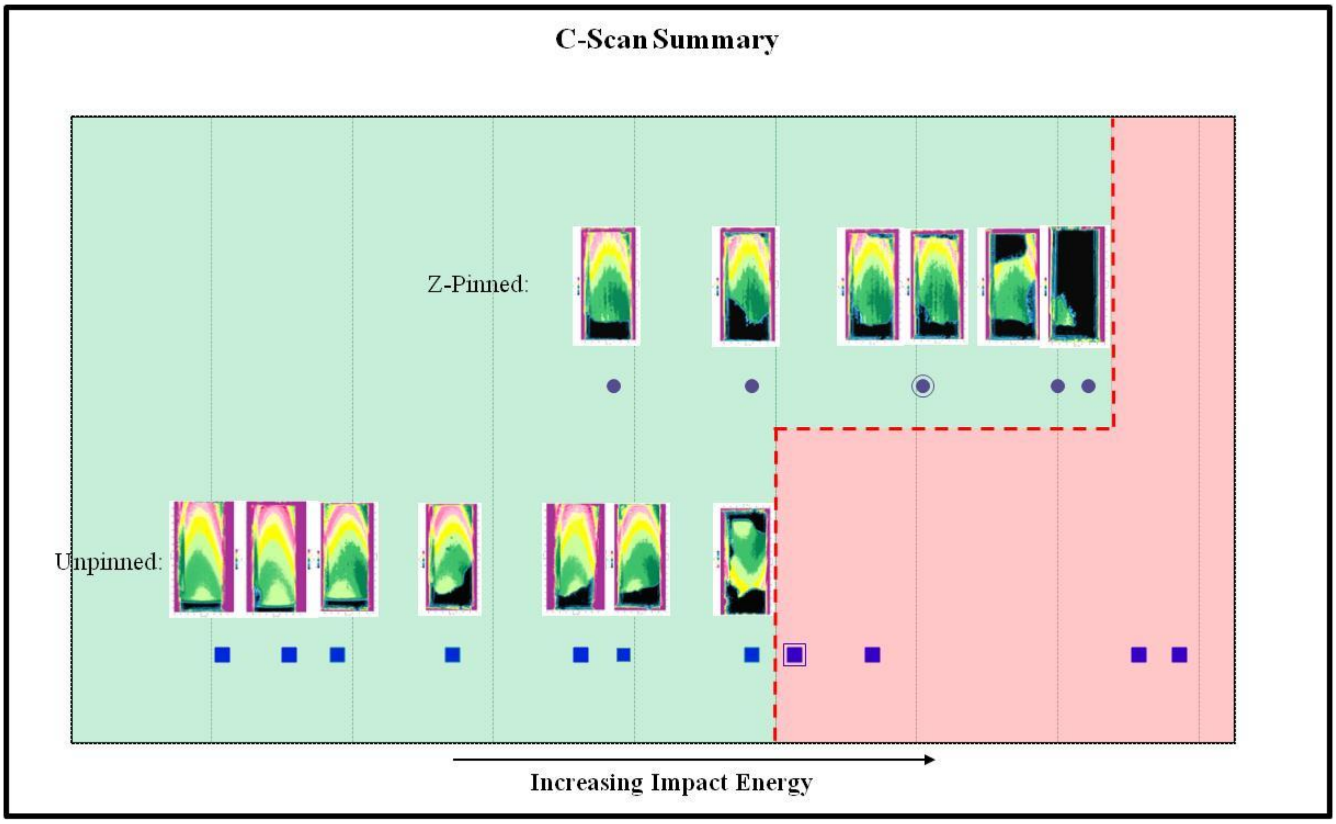

Figure 6. Summary of specimen c-scans and impact energy

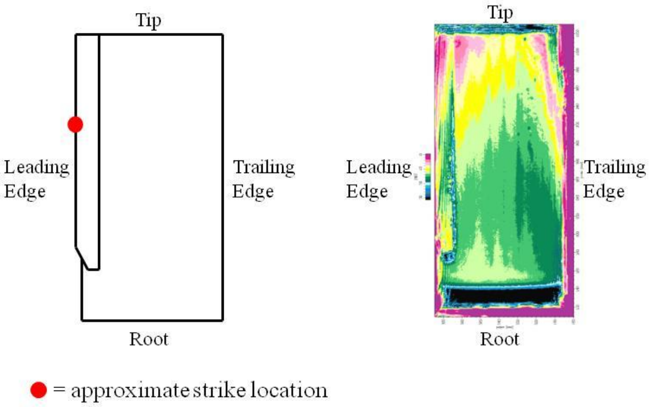

Figure 7. Orientation of specimen relative to c-scan

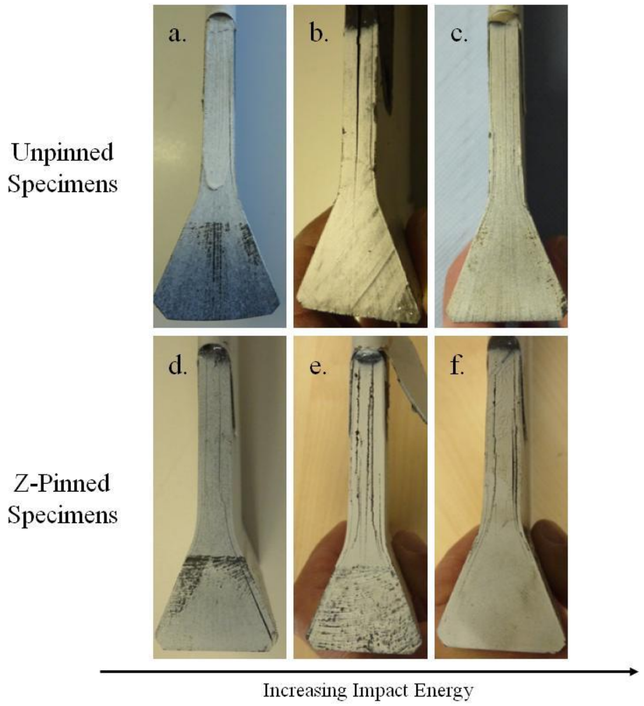

Figure 8. Leading edge root delaminations, unpinned vs fully pinned

Figure 9 shows example ct-scan sections taken through areas of delamination in a z-pinned specimen showing typical z-pin failure modes.

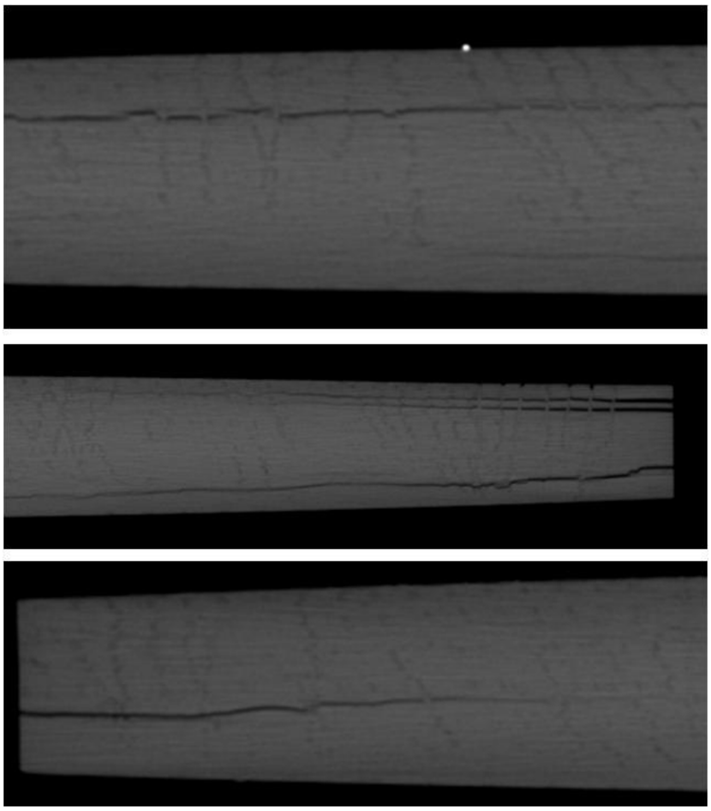

Figure 8. CT-scan images of z-pin failure modes

5 Discussion

5.1 Suppression of delamination

Figure 6 shows that it is possible to increase the delamination resistance of a structure subjected to bird strike loading through the application of z-pins. The z-pinned specimen resulted in an increase in the order of 20% in the threshold for complete aerofoil delamination when compared to the unpinned specimens. This increase in complete delamination threshold with z-pins is relatively small when compared to the increases in static Mode I & II fracture toughness values that have been previously reported, which have been shown to be up to 25 times greater in Mode I [6] and up to 7.5 times greater in Mode II [3], however it is more consistent with previous research carried out by Isa et al [7] on compression after impact (CAI) tests of pinned and unpinned laminates, which showed approximately a 40% reduction in delamination area following a 25J impact.

5.2 Z-pin failure modes

Figure 9 shows that some of the z-pins have failed in pull-out rather than tensile failure or shear-off. This failure mode was observed in areas of the blade that were approximately 9mm thick and is an interesting result as previous research has indicated that z-pins in thick laminates can break rather than pull-out due to the fact that the frictional pull-out load can exceed the tensile failure load of the pins [3].

5.3 Detrimental effects due to z-pinning

There were two key failure modes present in the specimens; the first failure mode to feature in each specimen type was a delamination occurring in the root transition region of the specimen, whereas the second failure mode was a delamination propagating from the tip of the specimen down the central plane of the specimen. The second failure mode only occurred at higher energy conditions, and quickly increased in extent with increasing energy in the unpinned specimens. The unpinned specimens which featured the aerofoil tip delamination showed a clear reduction in the severity of the root delamination when compared to the lower energy tests. This was due to the fact that the delamination, and subsequent reduction in stiffness, of the aerofoil close to the strike height resulted in an unloading of the root region.

The fully pinned specimens tested close to the unpinned specimen tip delamination threshold did not feature a delamination at the strike height due to the increase in delamination toughness in the aerofoil as a result of the presence of the z-pins. The absence of any significant damage at the strike height region of the fully pinned specimens meant that greater loads were transferred in to the root region, resulting in more excessive damage in the root region (i.e. multiple delamination planes in the root region). Reducing the damage in the aerofoil has therefore been achieved at the expense of the root region (see Figure 8); this could be detrimental with respect to a component design, since an aerofoil delamination is likely to be a more benign failure than a potential net section failure in the root.

6 Conclusions

It has been demonstrated that z-pins have the potential to reduce the delamination extent due to bird strike when compared to a 2D composite laminate. The ability to control the delamination extent potentially allows a component designer to use z-pinning to optimise structures for impact tolerance.

Acknowledgements

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