ANALYSIS OF THROUGH-THICKNESS REINFORCEMENTS EFFECT ON THE FAILURE MODES OF A COMPOSITE RIB FOOT

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ABSTRACT

This paper covers the evaluation of through-the-thickness reinforcements (z-pins) on the typical failure modes of a composite rib foot, such as interlaminar delamination at corner radii and fastener pull-through failure, under tensile loading conditions. The study assesses the practical difficulties associated with the z-pinning of curved components made out of CFRP, and the structural evaluation of plain and z-pinned L-Pull specimens ('L' shape specimens). The L-pull specimen was a component with up to 4% volume fraction (ρ) of local fibrous reinforcement inserted through-the-thickness of the specimen (z-pins). The initial failure for most of the unpinned and z-pinned specimens was delamination at the corner radii. Although z-pins did not seem to improve the initial failure strength of the component, they proved to be very effective in suppressing delamination growth. Overall, z-pinned rib-foot components were found to have similar damage resistance but considerably higher damage tolerance compared to the unpinned components.

1 INTRODUCTION

Through thickness tensile loading is developed when curved composite panels are subjected to a combination of bending and normal stress. Similar loading is generated where there is a change in load path direction, caused by a rapid thickening of the laminate, or a joggle, and resulting in a local moment. Through-thickness stresses can lead to delamination, which significantly reduce the performance of a structure under compressive or bending loads [1-2].

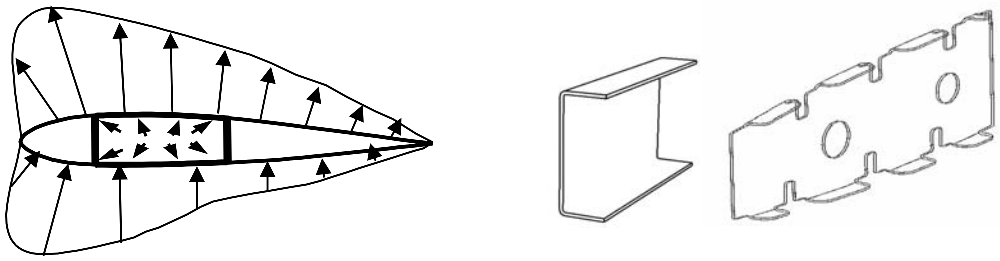
To overcome this problem, new composites with through-thickness reinforcement (TTR), such as stitching and z-fibre pinning (z-pinning) have been developed [3-5]. Several investigations have shown that z-fibres can offer significant improvement in fracture toughness, impact resistance and compression-after-impact strength [6-9], however, in order to maximise the effectiveness of z-pins a delamination crack has to propagate in their field for several millimetres [10-11]. This suggests that z-pins may be used to optimise the design of a composite structure with respect to the damage tolerance. As a trade-off z-pinned laminates may show a reduction in in-plane properties [5, 9, 12-13]. Previous studies so far, have been carried out at the coupon level [6-9], but recently the application of z-fibre has been investigated on aerospace sub-structural components [14-16].

This paper covers the evaluation of through-the-thickness reinforcements (z-pins) on the typical failure modes of a composite rib foot, such as interlaminar delamination at corner radii [17-20] or fastener pull-through failure [21-22], under tensile loading conditions. The study assesses the practical difficulties associated with the z-pinning of CFRP curved components and the structural evaluation of plain and z-pinned L-Pull specimens. The L-pull specimen was a component with up to 4% area density (ρ) of local reinforcements with two possible z-pin diameters (ϕ). The z-pins were inserted either in the corner region of the L-pull specimen or in the fastened area that is normally used for joining the rib to the aircraft spars and skins. The studies included an assessment of the influence of different z-fibre parameters and configurations on delamination growth and ultimate failure strength. The implications of z-pin utilisation are discussed in detail within the paper.

2 PROBLEM STATEMENT

2.1 Corner Radii failure in aircraft components

A common feature in aircraft structures where through-thickness loading is developed is a right angle flange such as a rib foot or spar flange. Tensile load applied at these elements (rib foot or spar flange) can be a result of either aerodynamic or fuel pressure loading or a combination of both (Figure 1a). Bending load also results from lateral loading reacted by ribs and parts of the spar, which provides tank boundaries for the main wing fuel tanks.



(a) (b)

Figure 1 *(a) Tensile loading carried by ribs and spars under fuel and aerodynamic pressure loading; (b) C-section composite components (spars and ribs).*

A typical design of ribs/spars is a one-piece C-section construction (Figure 1b). This configuration is simple, light and cost effective. However there are unresolved issues with monolithic composite C-sections: firstly the difficulty in controlling the flange's angle sufficiently during manufacture, which may affect the through thickness strength. The flange's angle quality depends on the tooling technique and is sensitive to manufacturing defects. Secondly, composite laminates have a low through thickness strength. In fact a driving design criterion for C-section flanges is to carry maximum tensile loading through the corner radii. A corner radii failure results in delamination, which may propagate and cause a stiffness drop and therefore a redistribution of the load to other parts of the composite structure. As an example, such phenomenon may occur in ribs with the presence of cleats (component which attaches stringer blade to rib web). For specific loading cases cleats will share part of the tensile loading with rib feet. Any delamination and reduction in bending stiffness of the rib feet will overload the cleats and therefore reduce its safety margin.

Composite components are already used in civil aircraft structures but, if the use of C-section composite components is to become more widespread, then the low through thickness performance at corner radii and consequent delamination failure needs to be addressed.

2.2 Z-pins large scale bridging mechanisms to stop delamination

Although the z-pinning technique does not seem to affect delamination initiation [11], it has proven to be a valid technique to arrest delamination growth [6-11]. During delamination growth z-pins provide crack closure forces that can delay and eventually stop delamination growth. Z-pin crack bridging enhances material resistance by partially shielding the crack tip from the applied delaminating loads [11]. When z-pin bridging mechanics takes place the extension of the bridging zone and the total crack length can become comparable, therefore the fracture analysis becomes a large scale

bridging (LSB) problem [11]. In order to activate the LSB process a delamination needs to propagate into the z-pin field for several millimetres; the LSB can then stabilise the crack growth and consequently raise the external load required to propagate the damage [11].
The ability of a composite structure to absorb the energy, reduces the damage development. The novelty with through-thickness reinforced composites is the large amount of energy absorption associated with the LSB process. For z-pinned composites the failure criteria for delamination growth becomes:

$$G \geq G_C + \Phi_{ir}$$

Where, G is the total strain energy release rate at delamination front due to applied load, G_c is the critical delamination toughness of the composite, and Φ_{ir} is the energy dissipation rate due to the irreversible LSB z-pin process. The last term in the above equation is the toughening mechanism of z-pinned laminates in terms of the fracture energy theory.

As previous studies have shown, delamination propagating from a corner radius in an L-Pull specimens is subjected to a mixed-mode loading condition [19]. Z-pins are, in general, more effective in stopping mode I delamination loads. If the crack is fairly advanced and the z-pins are allowed to rotate towards the mode II shear component without breaking, they can effectively resist both delamination modes. Finer pin diameters can enhance resistance against pullout failure, which is the typical z-pin failure mode under mode I loading conditions. Larger pin diameters are more resistant against shear failure, which is the typical failure mode under mode II loading condition [11]. In stopping delamination, alternative failure modes might be introduced in the z-pinned component, it is therefore important to assess the effect of z-pins mechanics on the failure modes of the composite rib foot.

3 EXPERIMENTAL DETAILS

3.1 L-Pull Specimens design and manufacturing

The L-Pull specimens (Figure 2) were manufactured from Hexcel AS4/8552 UD carbon prepregs. Three quasi-isotropic (QI) stacking sequences were considered, with three different laminate thicknesses (t) and two possible corner inner radii (r). Details relating to specimen type and geometry are reported in Table 1.

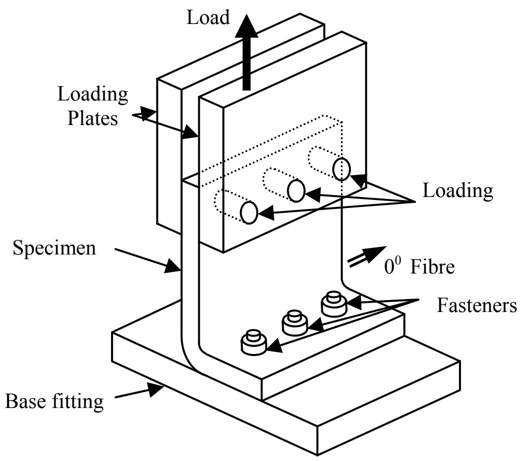


Figure 2 *Schematic diagram of the L-Pull specimen with the text fixture.*

The z-pins used were T300/BMI carbon pins with a diameter (ϕ) of 0.14 and 0.25 mm. The area densities (ρ) considered were between 0.5% and 4%. The z-pins were inserted prior to the laminate cure cycle. Z-pin configurations CR1 to CR3 (Figure 3) looked at the z-pin effect on corner radii delamination failure, with five fasteners in the horizontal section of the rib foot. Z-pins were inserted through the corner radius of the L-Pull specimen. Specimens for pull-through failure had only three fasteners in the horizontal section of the specimen. Configurations PT1 and PT2 were considered to assess the z-pin effect on the pull-through failure, with z-pins inserted only around the fastener holes with 2% (PT1) and 4% (PT2) respectively (0.51 mm pin diameter).

L-Pull Specimen Type	t (mm)	r (mm)	Layup [$0^0/\pm45^0/90^0$]
Plain/Z-pinned (CR1)	9	5	22/56/22
Plain/Z-pinned (CR2)	11	5	22/56/22
Plain/Z-pinned (CR3)	6.5	10	21.5/57/21.5
Plain/Z-pinned (PT1)	9	10	22/56/22
Plain/Z-pinned (PT2)	11	10	22/56/22

Table 1 *Test specimen details (3 specimens per type).*

Although within the corner, the area density of the z-pins changed through-the-thickness direction when the pins were inserted in a radial manner, the spacing of the pins on the outer laminate surface was still used as a reference to indicate the pin density.
For CR1 configuration, the specimen corner was heavily reinforced with z-pins. The radial insertion of the TTR was considered in order to align the z-pins with the direction of the main stress component σ_r which is thought to cause delamination failure in curved components. Z-pins fences were also considered on each side of the corner region in order to contain the delamination damage growth. The CR2 design was similar in concept to the previous one but considered a low z-pin density in the corner region. This design option was considered in order to limit the amount of resin rich areas in the corner region [5, 7,12].

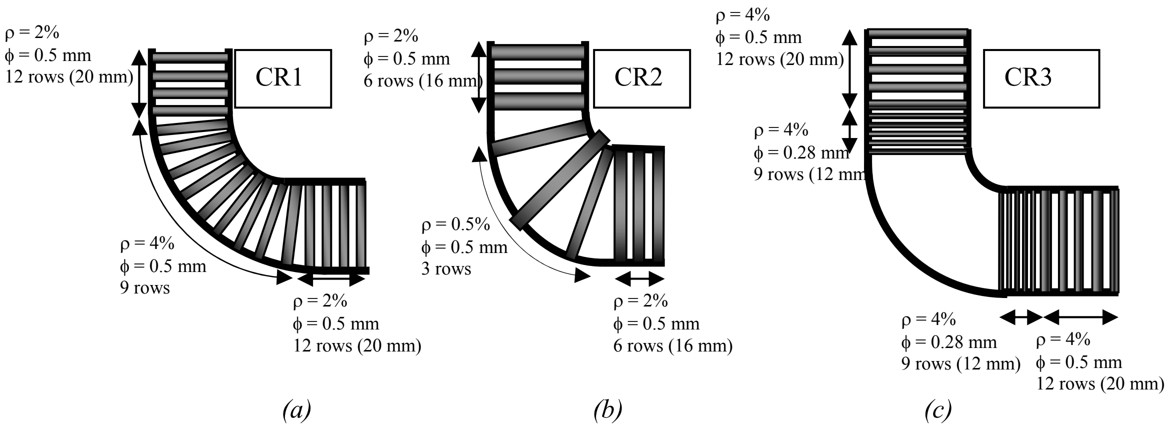


Figure 3 *Schematic diagram of z-pin configurations for the corner radii failure: (a) Configuration CR1 with the highest possible pin density through the corner; (b) Configuration CR2 with a 0.5% pin density in the corner; (c) Configuration CR3 for a damage tolerant design using z-pins.*

CR3 was produced as an optimised design aimed at improved the damage tolerance rather than damage resistance of the component. As stated in section 2.2, z-pins are more effective in delamination damage containment rather than preventing initiation [10-12]. It was therefore speculated that the initial delamination failure load would not be affected by the z-pin presence, therefore no z-pin was inserted in the corner region. Z-pin fences on each side of the corner were considered to stop delamination growth, once the delamination developed.

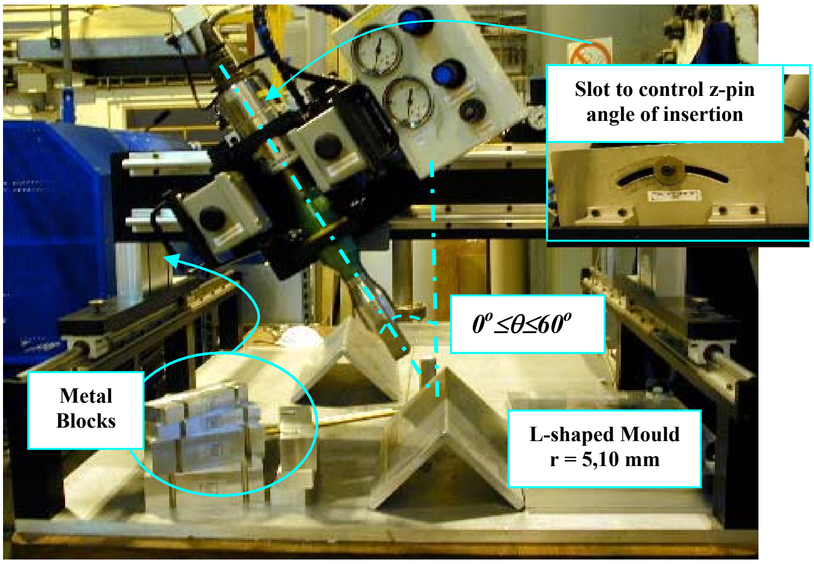


Figure 4 *Modifications of the z-pinning machine for z-pinning of curved components.*

A total of 30 specimens were manufactured. Of these 15 were reinforced through-the-thickness by z-pins. A z-pinning Ultrasonically assisted Vibrator (UV) was modified to allow z-pin insertion through the specimen corner radius. Details of the modified machine configuration are shown in figure 4.

The modifications permitted adjustments in the UV height and angle of inclination ($0^0 < \theta < 60^0$) in respect to the work-bench plane. In order to place the pins through the corner thickness in a radial configuration, single rows of pins were cut from standard pre-forms and were inserted using a multi-stage process. The quality of the z-pinning was assessed by cross-sectioning and polishing sample specimens. Sufficient pin penetration was achieved, although, in some cases, the pin angle of inclination of the cured component, was found to be slightly different from the original angle of insertion.

3.2 Experimental procedure

A schematic of the test fixture is also shown in Figure 2. The specimens were loaded in a displacement-control (1mm/min). After initial failure, the specimens were then reloaded for several additional loadings, each time reporting the delamination crack growth, pull-through occurrence or any other significant failure event. Optical inspection and c-scanning of the damaged specimens was also carried out to assess the extent of delamination.

4 RESULTS & DISCUSSION

4.1 Initial strength

The averaged initial failure loads for the different specimen configurations are reported in Figure 5. The specimens have been divided in 5 groups according to their thickness and corner radius value (LP1-LP5). Each group has z-pinned and unpinned specimens. Three ranges of failure strengths can be observed in Figure 5 regardless of the TTR configurations. Group LP1 exhibited failure strengths between 40 and 50 kN, groups LP2 and LP3 between 50 and 60 kN and groups LP4 and LP5 between 60 and 70 kN.
For group LP1 there was no significant variation of the failure strength between z-pinned (CR3) and unpinned specimens. This is consistent with the assumptions made in section 2.1 for delamination initiation. Group LP2-CR1 showed a knockdown of the failure strength. The z-pinned specimens CR1 exhibited the highest possible z-pin density at the corner radius. Within the corner radius the z-pin density increased radially towards the inner radius, it is thought that some of the resin pockets surrounding the pins might have coalesced into larger resin reach zones, which might have originated cracks under through-thickness stresses, hence the reduction in strength.

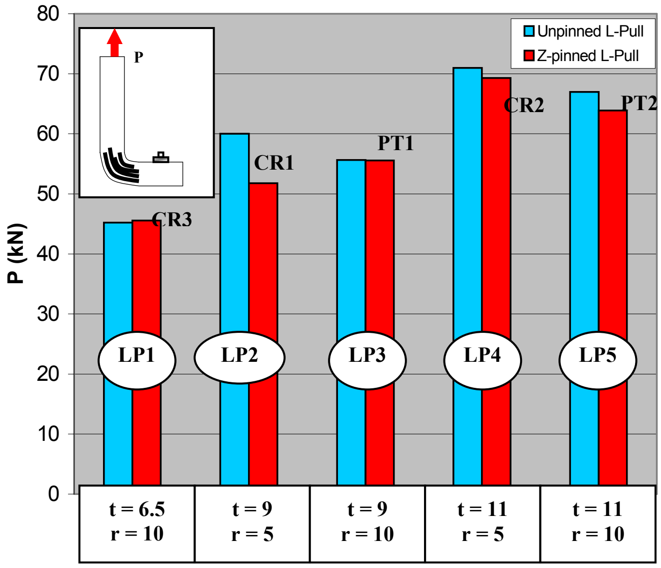


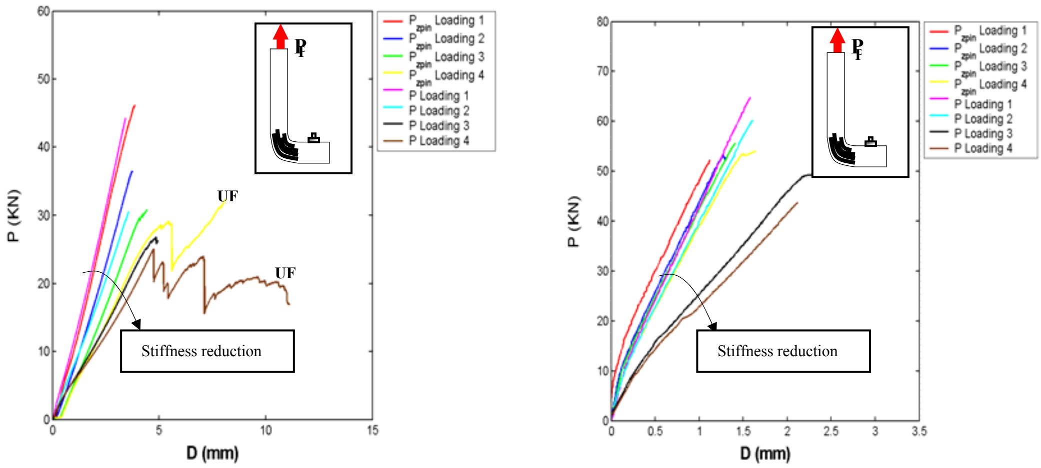
Figure 5 *Averaged initial failure strengths (P) for unpinned and z-pinned L-Pull specimens (t = specimen thickness, r = corner inner radius).*

Group LP3 presented similar failure strengths for both z-pinned (PT1) and unpinned specimens. The groups LP4 and LP5 did not show any significant variation of the failure strength between the unpinned and z-pinned specimens with configurations CR2 and PT2 respectively. The initial failure in all the specimens was delamination at the corner radius.

4.2 Mechanical performance after initial failure

As discussed in section 3.2 after initial failure all the specimens were reloaded for a series of loadings aimed to assess the z-fibre effect on damage growth and the residual stiffness/strength of the component. Figures 6 shows the load (P) against displacement (D) for two different specimens geometry and z-pin configurations.

The damaged z-pinned specimens appeared to be stiffer than the equivalent unpinned ones. For the initial loading (elastic field-no damage) the increased thickness due to z-pin insertion might have affected the global bending stiffness of the specimens [16]. Nevertheless from the graphs it is possible to distinguish a common trend even after damage propagation, with the z-pinned specimens retaining a high percentage of the original stiffness. For the unpinned specimens as delamination grew in an unstable manner the specimen stiffness was severely reduced.



(a) *(b)*

Figure 6 *Load (P) against displacements (D) during damage propagation for unpinned and z-pinned specimens: (a) LP1-CR3 (UF = ultimate failure); (b) LP2-CR1.*

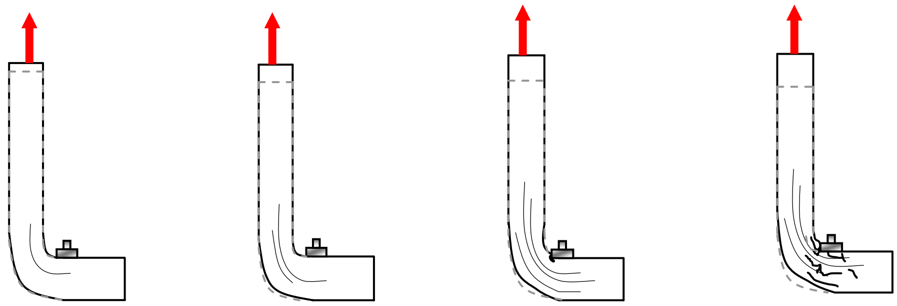
Z-pinned specimens of configuration CR3 (Figure 6a) seemed to be more effective in retaining the initial stiffness and strength of the unpinned specimen. For the subsequent runs with increasing level of delamination crack growth, the z-pinned specimens showed significant residual stiffness and strength. The ultimate failure load was also higher. Configurations CR1 (Figure 6b) and CR2 were more effective in retaining the stiffness once delamination initiated, indicating substantial damage containment.

4.3 Failure modes sequence

For the unpinned specimens the initial failure was found to be a single delamination at the corner radius covering the entire width of the specimen. A schematic of the failure initiation is depicted in Figure 7a. The position "through-the-thickness" and the length of this single delamination crack varied from specimen to specimen within the same group and from thickness to thickness between different groups. The delamination appeared to grow in a very unstable manner rapidly reaching the plane section of the specimen and the horizontal fastened area. For the z-pinned specimens the initial failure was either a single or a series of delaminations located within the corner radius.

For the unpinned specimens during the subsequent loadings, the delamination grew substantially, in addition multiple delaminations appeared through the thickness of the corner radius (Figure 7b). The delamination failure was very unstable and extended significantly towards the fastener holes and the vertical section of the specimen. For the z-pinned specimens delaminations already present in the specimens, were not seen to grow significantly, in addition if new delaminations appeared they tended to be small in length and confined within the corner region.

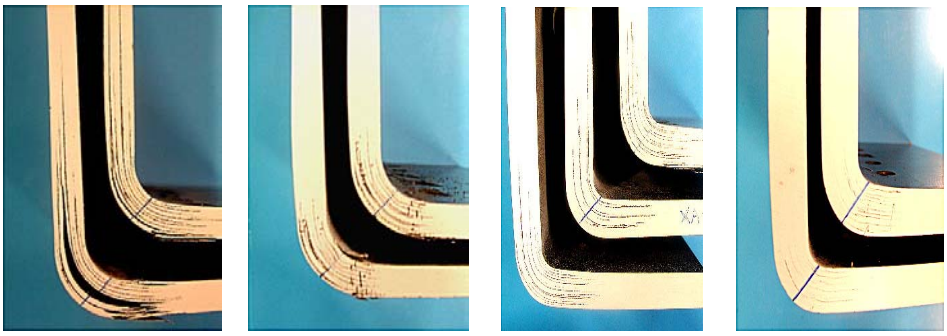
In the unpinned specimens due to the extent of delamination damage the bending stiffness in the corner radius was significantly reduced. Under the applied load the delaminated plies tended to align with the direction of the vertical load. At this stage the initial corner radius lost its original shape, leading to contact with the fastener heads (Figure 7c). Fibre breakage was therefore promoted at the outer edge of the fastener head, and the fastener heads became increasingly embedded within the specimen (Figure 7d). Localised splitting of the top and bottom surface plies and longitudinal cracks running through the line of fasteners were also visible.



(a) *(b)* *(c)* *(d)*

Figure 7 *Schematic of the failure sequence of the L-Pull specimen: (a) delamination initiation at corner radius; (b) multiple delaminations through the thickness of the specimens; (c) multiple delaminations growing towards the vertical and horizontal sections of the specimens and evidence of pull-through failure; (d) straightening of the corner radius with multiple delaminations, transverse matrix cracks and evident fibre breakage.*

The ultimate catastrophic failure was observed to be flexural in nature in the lower and upper plies near the fastener hole boundaries. Tests on z-pinned specimens gave evidence that the z-pins prevented further delamination damage growth and the subsequent ultimate failure load was redirected towards the fastener region. The restraint to delamination growth necessitated a change in the final failure mode, with the fasteners shearing through the upper plies of the specimen with consequent catastrophic fibre breakage.



(a) *(b)* *(c)* *(d)*

Figure 8 *Delamination cracks visible on the free edge of the L-Pull specimens: (a) Unpinned specimens (LP1); (b) z-pinned specimens (LP1-CR3). (c) Unpinned specimens (LP2); (d) z-pinned specimens (LP2-CR1).*

Figure 8 shows photographs of the LP1 and LP2 specimens. Multiple delamination cracks are visible on the specimen free edges. In figure 8a and 8c the delaminations propagated almost entirely through the vertical and horizontal sections of the unpinned specimens. In figure 8b delamination cracks were stopped at the z-pin fences for LP1-CR3 specimens. In figure 8d delaminations cracks were contained within the corner region for LP2-CR1 specimens.

With respect to pull-through failure, the visible damage to the laminate was restricted to a minor indentation (circular depressions) immediately under the fastener head, even for the specimens with only three fasteners (LP3, LP5). Previous studies [21-22] showed that damage resulting from pull-through failure of mechanically fastened composites was initially entirely embedded into the laminate with matrix cracks present through the thickness of the specimen. These cracks were found to initiate at the outer edge of the fastener head and propagate through the laminate thickness at approximately 45^0 to the laminate surface away from the fastener hole. The in-plane delaminations were found to be largely responsible for the pull-through damage extension.

It is thought that multiple in-plane delaminations propagating from the corner radius of the L-pull specimens denied the assessment of pull-through failure initiation. It is believed that the combined effect of the interacting forms of failure created a damage structure of considerable complexity within the fastener area. Delamination arrest due to z-pin bridging mechanics may have a beneficial role in containing pull-trough failure. However given the complexity of failure mode interactions in the fastener area, it was impossible to assess z-pin effect on this specific failure mode. Fractographic analysis of the failed specimens is continuing to ascertain failure sequence. Nevertheless the evidence of pull-through failure was observed in some of the tests, when the external plies were sheared through the thickness of the specimen. Evidence of transverse cracks running through the thickness of the specimens was also apparent on the inside surface of some of the fastener holes.

5 CONCLUSIONS

The effect of z-pins on the failure modes of a composite rib foot was investigated. The research study included an assessment of the influence of different z-fibre parameters and configurations on the initial and ultimate failure of L-Pull specimens. Several L-Pull specimen configurations with through-thickness reinforcements were designed, manufactured and tested. The study also assessed the practical difficulties associated with z-pin insertion through CFRP curved components.

The initial failure for both unpinned and z-pinned specimens was delamination at the corner radii. Although z-pins did not seem to improve the initial strength of the component, they proved to be very effective in stopping delamination growth. The damaged z-pinned specimens retained considerable stiffness and as a result of controlling delamination failure, the ultimate failure load was higher than in the unpinned specimens.

A design philosophy aimed to implement the use of z-pins into aerospace composite structures may be appropriate as a method of improving damage tolerance.

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