TENSILE PERFORMANCE OF FIBRE-ORIENTED SCARF REPAIR COUPONS FOR WING SKIN MATERIALS

Robert S. Pierce[1] and Brian G. Falzon[2]

[1] DTU Wind and Energy Systems, Risø Campus, Frederiksborgvej 399, 4000 Roskilde, Denmark, rsapi@dtu.dk

[2]School of Engineering, RMIT University, PO Box, 2476, Melbourne, 3001, Australia. brian.falzon@rmit.edu.au

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ABSTRACT

Bonded scarf repairs are attractive for large composite aerostructures due to their high performance and low weight compared with mechanical fastening methods. However, the scarfing process requires considerable time and expertise in the removal of undamaged parent material to which a repair patch is bonded. New portable and automated scarfing machines aim to address this issue while improving reliability and allowing for more complex and efficient repair designs.

In this work, the tensile performance of novel fibre-oriented scarf repair coupons has been investigated. Non-destructive inspection and microscopy confirmed the viability and quality of a matched-ply approach for this type of complex repair design. Tensile testing revealed minor differences between the performance of size-optimised and strength-optimised fibre-oriented scarf repairs, which both behaved similarly to the conventional scarf design, reaching over 65% of the pristine laminate strength. However, analysis of the failure behaviour, loading curves, and fracture surfaces suggest that coupon failure initiates prematurely in the outermost parent plies rather than in the repair. This, and potential issues related to load application and the parent residual strength, are all discussed with recommendations for improved testing of repair joints in the future.

1 INTRODUCTION

Adhesive bonding methods for the joining and repair of composite structures offer several benefits over traditional mechanically fastened patch methods [1]. Greater repair efficiency, a minimal change to the surface profile of the structure, and the avoidance of drilling-induced damage are all significant advantages. External bonded patch repairs are the simplest to apply [2], although in practice they are typically reserved for thinner sections (up to 3 mm thick). For thicker structures, a scarf or step repair design is more commonly implemented [3]. Such repairs generally exhibit a matched stiffness to the original structure, along with the highest joint efficiency of any repair method [4]. However, this requires significant removal of the parent material in order to achieve the shallow repair taper necessary for optimal load transfer, along with a high degree of practical expertise. Hence there is considerable interest to optimise the design of adhesively bonded scarf and step repairs to reduce the repair size without compromising performance.

1.1 Important factors in repair design

A number of key design parameters, such as taper angle, stacking sequence, and use of protective over-plies, can greatly affect the performance of bonded scarf repairs. Fundamentally, for aerospace applications with high-performance carbon fibre-reinforced polymer materials, a taper angle of 1° to 3° (around 60:1 to 20:1) is typical [5]. However, the selection of this scarf angle is always a trade-off between adhesive strength for shallow angles and parent residual strength (after material removal) for steep angles [6]. In many applications, a perfectly flush scarf repair is not sufficient to restore the full design capabilities of a damaged structure. Hence, external patches, or 'over-plies', are added to the repair design for additional strength and protection of the scarf tip (where adhesive stresses are highest and the repair patch is thinnest) [4]. In relation to stacking sequence, a previous parametric investigation for 5° scarf repairs showed a relatively low sensitivity of the adhesive stress to mismatched plies, and a large reduction in peak stresses with use of over-plies [7]. Additionally, tensile failure modelling and experimental testing of a 2.85° (20:1) scarf repair revealed that the use of optimised stacking sequences (not simply 45° variations) in the repair patch could also result in 85% and 90% strength restoration for flush and single over-ply repairs respectively [8]. Ultimately, most of the above work has focussed on simple repair designs with a conventional circular shape and uniform taper angles without considering more efficient.

1.2 Optimisation of repair shape

Although, the optimisation and modelling of bonded repairs for aerospace composite structures has been recently reviewed [9], several works should be discussed here as they are of particular relevance to this research. Additionally, new technologies have emerged, like automated portable scarfing machines, that can significantly improve the efficiency and reliability of scarf repairs [10]. These also create the opportunity for more complex repair shapes and designs that would not be possible to prepare by hand. Early work in the optimisation of scarf repair geometry has investigated a concentric ellipse shape for orthotropic structures, where the elliptical aspect ratio is equivalent to the biaxial stress ratio [11]. The same work also extended design consideration to a hybrid square-ellipse shape for high aspect ratio repairs, where material removal could be reduced by 26-76% while retaining near-optimal performance. More recently, elliptical shape repairs have again been studied to reduce material removal requirements by as much as 41% in panels with a 4:1 biaxial stress ratio [12]. Alternatively, Niedernhuber et al. developed a novel ‘fibre-oriented’ step repair to take advantage of composite laminate anisotropy by reducing the step length (and bonding area) between off-axis plies [13]. Using step joint coupons and numerical modelling, the improved stepping design was found to reduce the joint length by over 40% for the same strength as a conventional step joint [13]. Other work has considered a similarly-optimised scarf joint, with a 30:1 taper for 0° plies and a 2:1 taper for the remaining off-axis plies, against a conventional 20:1 design [14]. Their results show a 60% reduction in joint length with only a 36% reduction in strength.

Lastly, previous work by the authors has focussed on a similar fibre-oriented scarf design, where the taper of off-axis plies reduces depending on the angular deviation from the loading direction [15]. Analytical modelling of this design showed a reduction in scarf repair size by up to 36% in a quasi-isotropic laminate, without compromising strength. Additional finite element analysis with a cohesive zone model for bonded scarf repairs of various designs also supported these theoretical results. For example, a 33% reduction in scarf area, or a 17% increase in strength, were predicted using a fibre-oriented scarf design compared with conventional scarf designs of the same strength or size respectively [15]. Although the modelling approach was validated against existing results for real bonded repairs, experimental testing of the fibre-oriented scarf design was missing from the study, with its overall practicality remaining a significant question. Subsequently, this work endeavours to experimentally assess the feasibility and performance of such complex fibre-oriented scarf repairs.

2 REPAIR SAMPLE PREPARATION

2.1 Repair design

Fibre-oriented and conventional scarf joint coupons were prepared for tensile testing and analysis. Although equivalent 2D joint testing is often considered to be more conservative than real 3D repairs [8], it is a useful first case for the comparison of different repair configurations. The samples in this case were designed to be representative of a matched-ply, partial depth (33%), repair in a thick wing skin laminate (see Figure 1). This partial-depth and asymmetric configuration was chosen to avoid the machining and size demands of a full thickness repair. Additionally, CNC machining of these materials to a very thin tip, in the case of a full-depth repair, can produce considerable vibration and subsequent machining tolerance issues that are not the focus of this study. Ply-matching for the repair patch, although often considered practically difficult [16], was selected for this work as it has long been a common recommendation for repairs [5]. A 30:1 scarf taper was used as the conventional scarf baseline. Two fibre-oriented scarf repair configurations were also studied:

- *Size-optimised*: maintaining the same minimum taper of 30:1 between 0° plies.
- *Strength-optimised*: maintaining the same relative length as the conventional scarf.

Details of the taper design for different ply orientations can be seen in Table 1. In both fibre-oriented scarf designs, the ±45° plies have steeper taper angles to reflect the lower loads that are expected to transfer through them. Furthermore, a butt joint is simply used between the 90° plies. Due to a relatively low number of 90° plies, and the same additional over-plies being used in all three cases, the overall length reduction using the size-optimised design in this work was only around 20%. This complex scarf design has also been extended to a 3D scarf demonstrator, for the same depth in the same parent material [17], where the overall scarf size reduction was closer to the 36% limit [15].

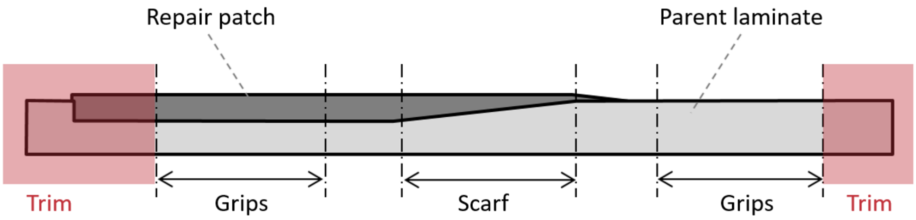

Figure 1: Scarf repair coupon configuration.

Repair configuration	Machined taper angles			Relative scarf length
	0° plies	**±45° plies**	**90° plies**	
Conventional scarf	30:1	30:1	30:1	100%
Size-optimised scarf	30:1	21.2:1	-	80.9%
Strength-optimised scarf	38.5:1	27.2:1	-	100%

Table 1: Scarf tapers for the different ply orientations in each repair configuration.

2.2 Coupon preparation

The representative parent laminates consisted of Non-Crimp Fabric (NCF) layers internally, with a woven ply at each of the exterior surfaces. After milling each desired 33% depth scarf design on a 3-axis CNC machine, the repair area was sanded and cleaned to produce a more reliable bonding surface. The soft repair patches were prepared following a matched-ply method (representative of industry standards); using unidirectional (UD) and woven prepreg plies, a film adhesive for the bond-line, and regular vacuum-assisted debulking steps. A combination of UD and woven prepreg over-plies were also used to protect the exterior scarf tip. The repaired panels were then cured in place, within a vacuum bag in an autoclave, based on material specifications. A minimum of five, 250-300 mm long and 25 mm wide, coupons were finally cut from each different repair panel in preparation for tensile testing.

2.3 Repair assessment

The quality of the repaired panels was confirmed by through-transmission ultrasonic scans seen in Figure 2. In the absence of any large bond-line defects, these repairs were classified as of good quality. Bond-line microscopy showed accurate ply stepping and good ply matching, with only a small offset in the thickness direction due to the adhesive film thickness at the bottom of the repair patch. Image analysis also reveals the standard deviation of plies from their nominal spacing to be less than ±0.5 mm. Detailed stitched images of the conventional, size-optimised, and strength optimized scarf repairs can be seen in Figure 3, Figure 4, and Figure 5 respectively.

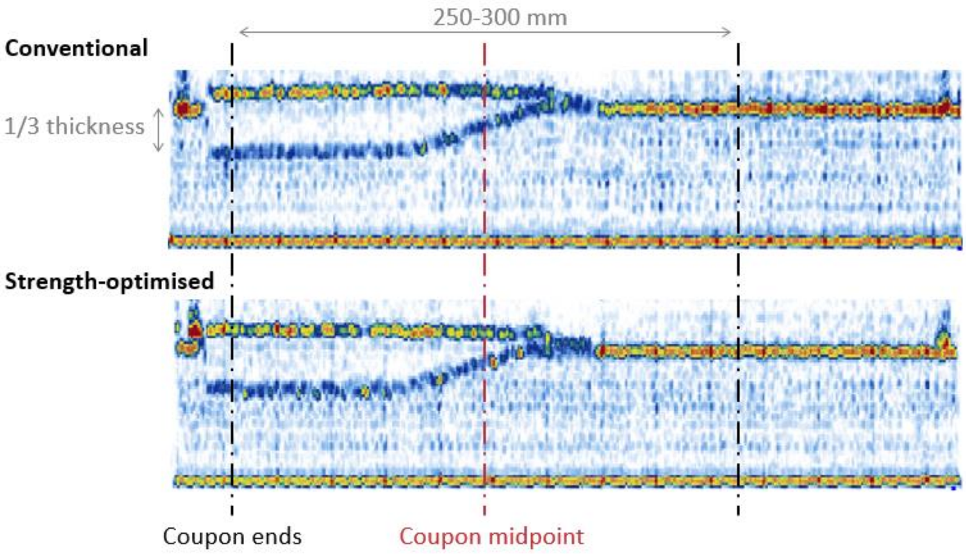

Figure 2: Representative ultrasonic B-scans of conventional and strength-optimised repairs.

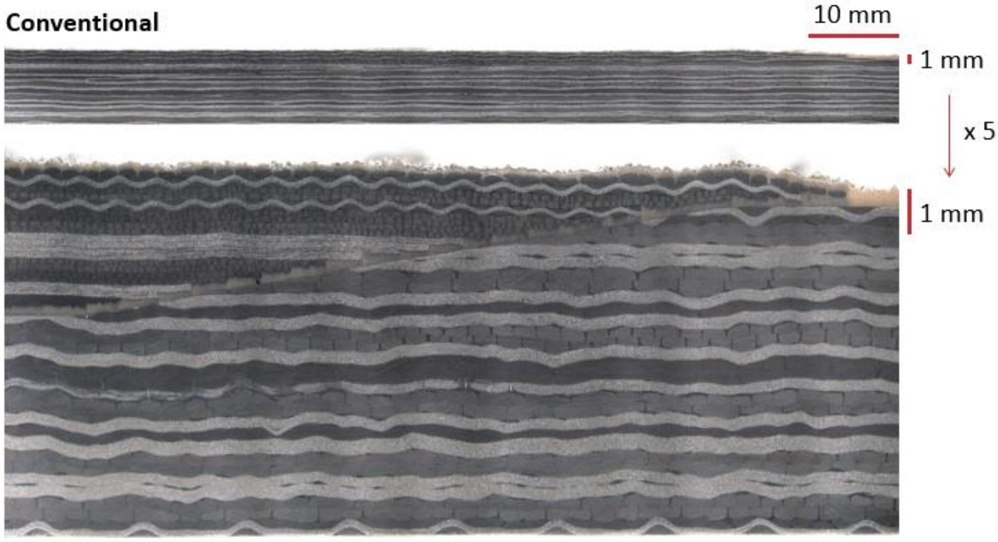

Figure 3: Conventional scarf repair bond-line, including 5x height-stretched visualisation.

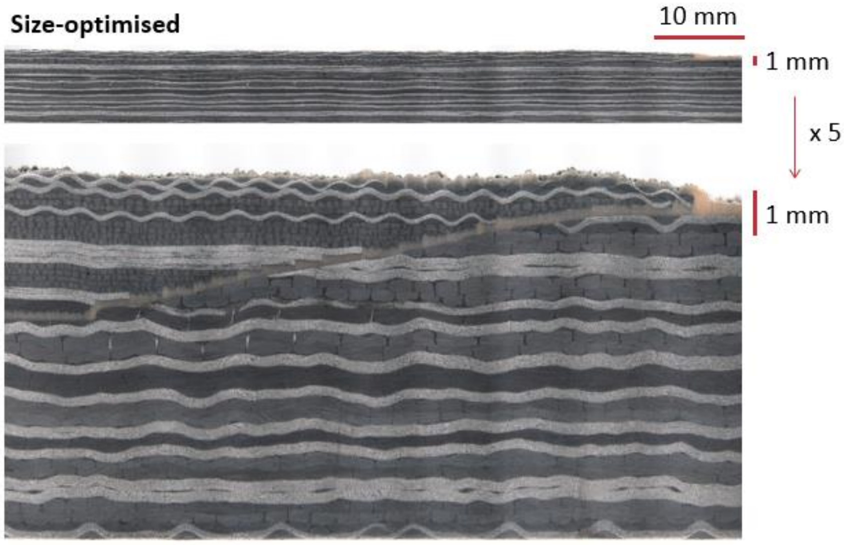

Figure 4: Size-optimised scarf repair bond-line, including 5x height-stretched visualisation.

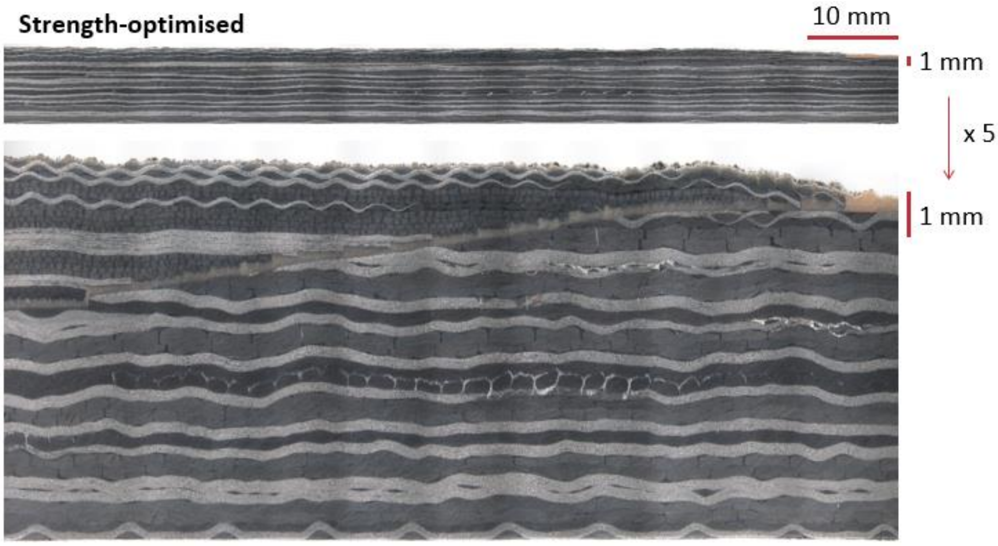

Figure 5: Strength-optimised scarf repair bond-line, including 5x height-stretched visualisation.

3 TENSILE TESTING

3.1 Failure loads

Tensile testing was performed at a constant rate of extension, around 1 mm/min, on a universal testing machine with hydraulic clamps to prevent sample slippage. The resulting load-extension curves were very consistent among each batch of samples, with the fibre-oriented scarf coupons performing similarly to the conventional scarf samples.

Although the location of each specimen failure was not always consistent, all samples appeared to fail as a result of the exterior woven parent plies reaching their strain limit. In most cases, this would initiate failure in the adhesive bond-line or through the repair patch, with the woven ply on the pristine side of the samples failing at the same time (or not long after). Then loading would resume until the residual parent laminate failed completely. Figure 6 shows two load-extension curves that are representative of all tests; with either two or three peaks, depending on whether the back surface woven ply and repair patch failed simultaneously or not. Here the load values have been normalised relative to the pristine parent failure loads, with the repair samples generally failing above 65% of the parent laminate strength. The mean normalised failure loads for each repair configuration, and the different failure peaks, can be seen in Figure 7. Overall, there is little difference between the results of each batch, and they all appear to lie within the experimental scatter. Although, the initial failure in the size-optimised fibre-oriented scarf repairs may be failing more consistently at the lower end of this scatter. Considering that this repair is physically the shortest, despite the idealised theory that suggests it should result in similar strength, it is not unlikely that this case would fail at lower loads. However, there is not a statistically significant difference between the results.

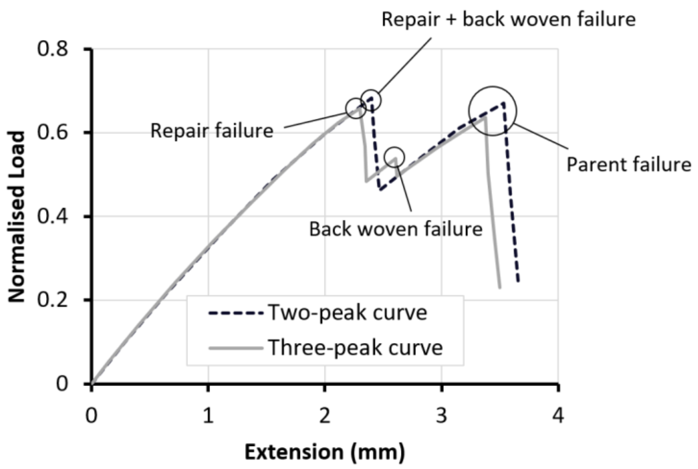

Figure 6: Normalised tensile load-extension curves for the two behaviours representative of all repair coupons.

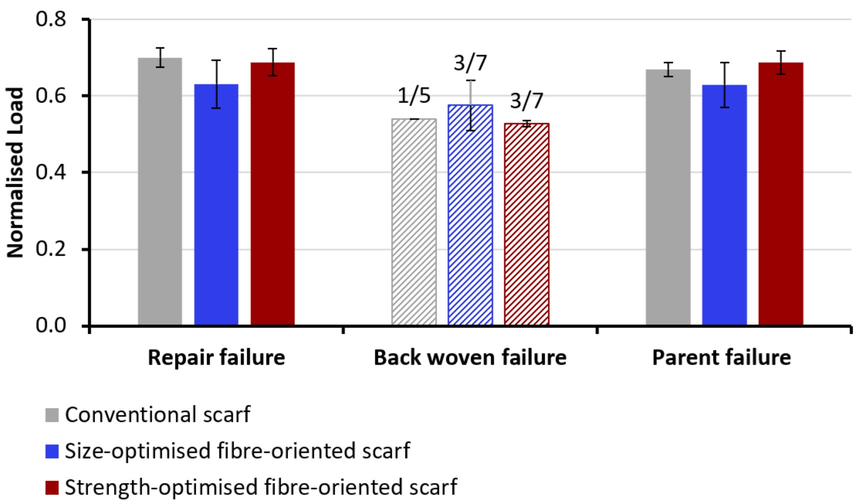

Figure 7: Normalised failure loads for the different repair configurations (related to the failure peaks in Figure 6). Back woven failure was only observed in a subset of the samples, as labelled.

3.2 Fracture analysis

Visual observation of the failed samples revealed inconsistency in the location of failure for each coupon batch. As can be seen from the size-optimised repairs, shown in Figure 8, the repair-side failure sometimes surfaced through the middle of the patch, suggesting a composite failure, and sometimes at the tip of the repair, which might suggest bond-line failure. However, microscopy of one fractured scarf repair, not tested to complete parent failure (Figure 9), highlights an initial tow failure that occurs in the woven plies of the parent laminate. In this case the tip of the patch over-plies have cleanly disbonded from the parent laminate, but it appears that failure both initiated and travelled along the woven ply underneath the bond-line, rather than purely through the adhesive bond-line as might be expected. Similar observations can be inferred from many of the other samples, which also showed significant fractures among the parent woven plies.

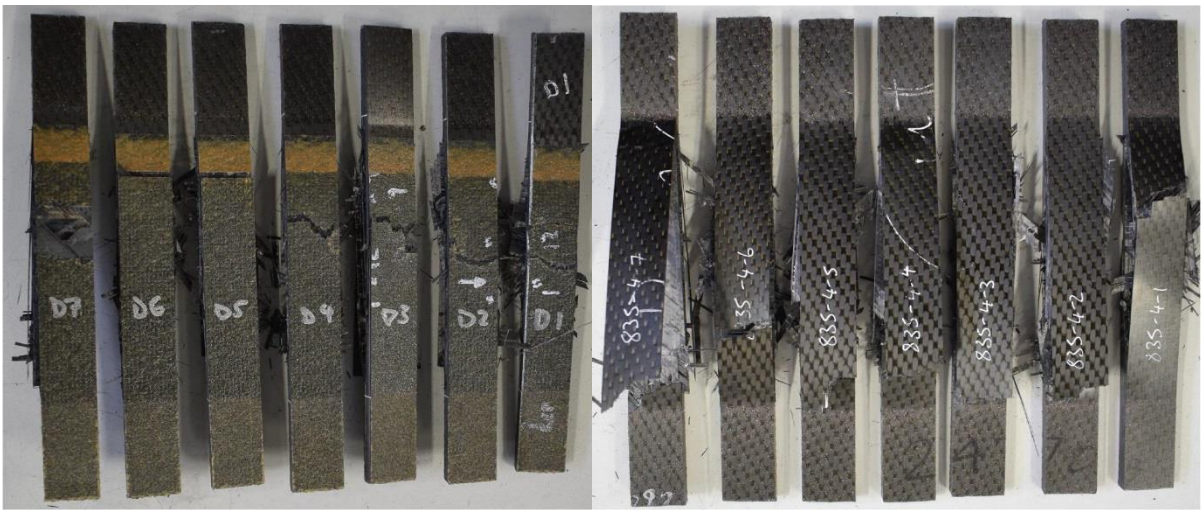

Figure 8: Front (left) and back (right) surfaces of the failed size-optimised fibre-oriented scarf repair.

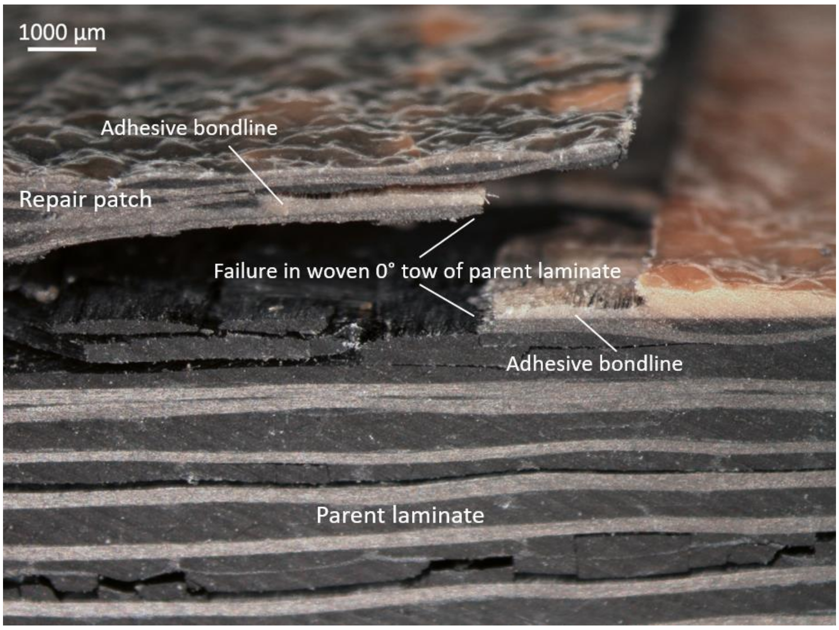

Figure 9: Microscopy of first failure, initiated by exterior woven ply of parent laminate.

4 CONCLUSIONS

This work serves as a proof-of-concept for complex fibre-oriented scarf repairs, demonstrating that they can be conducted to the same standard as conventional scarf repairs with good ply matching. However, further work is required to better assess the performance of these novel repair configurations. The tensile testing results from this study were inconclusive since the outer woven ply failure, parent failure, and repair failure were all observed to occur at similar loading (around 66% of the pristine strength). Hence, it was not possible to isolate the response of the repair patch from the possibility that the woven ply was causing all failure initiation, or to determine any strength recovery that might result from the repair. The loading conditions, where one end of the repair patch itself was clamped, were also identified as a potential source for misleading results, since this scenario forces unrealistic stress and strain through the patch.

Subsequently, three possible adjustments are proposed for mechanical testing in order to evaluate these types of repairs:

- Firstly, longer samples of the same materials could be manufactured with a complete transition from parent-patch-parent, such that only the parent ends are clamped and load can redistribute more naturally around the patch.
- Secondly, it would be beneficial to manufacture laminates and patches entirely from the same unidirectional material to avoid the early failure of the outer woven plies that may be compromising any benefits of the repair.
- Lastly, it may be valuable to consider an alternative repair depth, since the ultimate load of the residual parent material closely matches those of the repair and woven plies, and further disguises any differences between the samples.

Any combination of these changes could be adopted for the next round of testing in order to achieve more meaningful results.

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