Influence of double vacuum debulking process on co-cured soft-patch carbon fibre composite repairs

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Abstract

Reliable composite repair processes are a necessity to support the operation of next generation lightweight commercial aircraft. In-situ soft patch repairs of aerospace structures made from carbon fibre reinforced polymers require curing of conventional autoclave prepreg materials in an out-of-autoclave environment, which can result in poor repair quality. We demonstrate that the use of a double vacuum debulking (DVD) pre-curing step for soft patch repairs can essentially achieve void-free repairs for prepreg materials with moderate to high solvent residue. Porosity reductions translated into an increase in flexural and interlaminar strength properties of 7.3% and 14.8%, respectively. The repair quality improvement due to void reduction in both soft patch and adhesive film resulted in a 19% increase in tensile repair strength. The work presented demonstrates the need to include a DVD pre-curing step to achieve the stringent manufacturers’ repair porosity limits and performance requirements for highly loaded composite aircraft structures.

Keywords: A: carbon fibre; B: porosity; B: strength

1 Introduction

Current and next generation commercial aircraft are designed to be increasingly lightweight to meet stringent environmental restrictions on emissions and to improve fuel efficiency. Aircraft designs such as Airbus 350XWB and Boeing 787 Dreamliner contain approximately 50% composite materials by weight [1]. A significant percentage of this applies to the replacement of conventionally used metallic materials for primary and secondary structures, such as aluminium alloys for the fuselage and wings, by carbon fibre reinforced polymers. While carbon fibre composites have many advantages such as high specific strength, stiffness, corrosion resistance and fatigue properties [2], they can be highly sensitive to temperature, moisture and impact damage [3, 4]. Additionally, the high cost of replacing large composite sections in the case of damage or structural modification necessitates the development of on-site repair strategies [5].

Reliable and cost-effective out-of-autoclave (OOA) repair processes that can achieve high repair quality, e.g. low porosity and high strength, are required by aircraft manufacturers and the maintenance, repair and overhaul (MRO) industry [1]. For highly loaded aircraft structures, scarf repairs are of particular interest due to the flush surface finish, which does not disrupt the aerodynamic outer surface features and restores strength due to the large adhesive bonding area [6]. Consequently, there has been significant research focus on developing novel repair manufacturing processes to minimize porosity, particularly in soft-patch repairs [5]. In a soft-patch repair, uncured prepreg plies are cut to fit the scarf cavity in a controlled environment, shaped to the underlying structural geometry and then co-cured with a film adhesive directly on the aircraft structure. In contrast, for the moulded or machined hard patch method, the patch material is cured in an autoclave prior to curing onto the aircraft structure [7] with similar film adhesive materials and curing cycles as for the soft patch method.

The soft patch approach is considerably less expensive and requires only portable equipment for OOA cure for on-site aircraft repair. The main issue faced here is the achieving of high strength and low porosity repairs. This requires eliminating temperature and moisture effects, as well as ply distortion or wrinkling during consolidation. Porosity can be caused by a range of factors such as adsorbed moisture, entrapped air, residual solvents, or reaction by-products during resin cure [5]. Residual solvents may remain present in moderate amounts of 7-10% if prepreg systems are manufactured by solution dipping. This prepreg manufacturing process works with a matrix resin dissolved in a volatile carrier, allowing for good penetration of the low viscosity solution into the reinforcing fibre bundles when fibres are pulled through the resin bath [8].

Several prepreg manufacturers have introduced specially formulated prepreg systems to achieve high quality OOA-cured composites such as the Hexcel M56, Cytec 5320 and Toray 2510 [9]. However, the application of dissimilar repair materials to the parent structure is currently prohibited by original equipment manufacturer (OEM) repair specifications even though the mechanical performance is satisfactory [10]. This is because the cost of material qualification for aerospace use is restrictive [11].

To improve volatile depletion for OOA cure of traditional aerospace prepreg composites, the double vacuum bag debulking (DVD) process was first demonstrated in 1983 by Buckley et al. [12], and comprises of a second vacuum bag over a rigid enclosure on top of the existing vacuum bag lay-up. DVD is a pre-curing stage of the prepreg patch material only and is typically performed away from the parent structure in a controlled environment. The basic principle of the DVD process is to apply a vacuum pressure on the prepreg material without the compaction force on the vacuum. As the upper vacuum chamber is evacuated, the consolidation force on the prepreg in the lower bag is reduced and a pathway for the volatiles to escape is made available, allowing the volatiles or reaction by-products to be degassed in a shorter time [13,14]. Since its first introduction, the DVD process has been further developed and demonstrated for several prepreg resin systems [15-17]. Some studies have reported conflicting results on the use of the DVD process, particularly on low viscosity resins, due to excessive resin bleed-out causing high void content and poor wetting of the fibres [18].

The authors recently demonstrated the beneficial effect of the DVD process for a hot melt prepreg system, which contained a relatively small amount of solvents and showed that porosity can be mostly eliminated with combined DVD processing and OOA cure [19]. However, less is known about the influence of the DVD process on prepregs manufactured with the solution dipping process, which may have a solvent content of up to 50% during the prepreg manufacturing process before drying. While hot melt processes continue to hold a larger prepreg market share and are generally cheaper and faster [20], certain resin formulations, such as low temperature curing systems [21], cannot be handled in this way. Solution dip methods are also preferred for fabric prepregs to avoid weave distortion during hot melt pressing of resin films into the fabric [8].

This experimental paper studies the effect of the DVD process on the quality and mechanical properties of carbon fibre reinforced polymer repairs for prepreg systems manufactured by the solution dip process. The prepreg material in this study contains 3 to 7% acetone as per manufacturer's datasheet [22] and is certified for secondary aircraft structures. Benchmarking of the repair properties with DVD process is performed against standard single vacuum cure (SVC), which locally can result in up to 20% ply porosity depending on repair configuration. The location and influence of porosity in the composite and adhesive film on the mechanical patch and repair properties are investigated through microscopic analysis, X-ray micro-CT and detailed experimental testing. The repair strength and failure modes in coupon level tests are also compared against the autoclave properties and open-hole tension strength. The research outcomes presented highlight the achievement of realizing consistently high repair quality in any investigated configuration using the DVD process in combination with an OOA manufacturing process.

2 Experimental methodology

2.1 Materials and manufacturing details

Composite laminates were manufactured from T300/Cycom 970 carbon/epoxy plain weave 3K woven prepreg plies (Cytec Industries Inc.). For the autoclave property benchmark and repair parent laminates, the composite material was cured in an autoclave in accordance with the manufacturer's recommended cure profiles (177˚C for 150 mins). An eight ply unidirectional lay-up $[(0/90)]_8$ was used for all laminates and a nine ply unidirectional lay-up $[(0/90)]_9$ for repair studies in this work, resulting in approximately 1.8 mm and 2 mm composite thickness, respectively. The film adhesive used for the repair process was a Henkel PL7000 film certified for aerospace repair with a non-woven polyester scrim resulting in a nominal thickness of 200 µm.

The "single vacuum cured (SVC)" specimens refer to standard vacuum bag curing in an OOA environment. A heat blanket is used to heat the specimens with the same curing profile as for the autoclave process. The "double vacuum debulking (DVD)" specimens refer to those that have undergone a prior B-staging step. The layup for the DVD step is shown in previous work [19]. The temperature cycle involves a ramp rate of 1°C/min to 93°C, followed by a hold of 30 mins. The upper vacuum is then vented and the temperature is held for a further 30 mins, then cooled to room temperature. After the DVD cycle, the patch is then transferred to the panel and cured with the same full cure cycle as the SVC specimens.

2.2 Composite laminate and repair testing

Test specimens and composite repairs of various arrangements and geometries were manufactured as illustrated in Fig. 1. All specimens were cut from the composite panels using a waterjet cutter. For each test configuration at least five specimens were tested to determine average strength and experimental standard deviation.

Fig. 1a shows a standard composite in (0/90) patch configuration. The 1D repair specimens in Fig. 1b were laid up similarly to the patch laminates with the addition of one layer of film adhesive at the bottom. This configuration has a significant effect on the porosity distribution and content - as will be discussed later - as the film adhesive material cures at a faster rate compared to the patch. Tensile tests (ASTM D3039 [23]), 4-point bend flexural tests (ASTM D6272 [24]) and short beam interlaminar shear tests (ASTM D2344 [25]) were conducted on the patch, 1D repair and autoclave laminates.

Tensile tests were performed on the scarf lap joint and 2D scarf repair specimens depicted in Figs. 1c and 1d. Both specimen types have a bond length of 57.3 mm, as a result of the scarf angle of 2°, which was machined by milling. The scarf lap joints and 2D repairs were cured as larger test panels, which were then cut into the correct width to reduce excessive resin bleed-out via the specimen edges. Glass fibre end tabs of 3 mm thickness were bonded to the grip areas for the scarf lap joints and 2D repairs to reduce failure at the grips.

The scarf lap joints (c) had a width of 25.4 mm. The scarf lap joint tests were conducted to evaluate the strength of a bonded repair without porosity and resin-rich areas affecting the quality of the patch. This essentially represents a hard patch approach and allows for the evaluation of the properties of the film adhesive when bonding two previously cured composite adherends. The 2D scarf repair specimens (d) represent coupon level tests for a soft patch composite repair. The 2D scarf repair specimens were manufactured with a 25 mm gap between the parent substrates, representing a 25 mm sized initial damage. The 2D scarf repair specimens had a larger width of 50.8 mm to minimize alignment errors of the soft patch material.

The open-hole tension strength of the autoclave laminate was measured in accordance with ASTM D5766 with a hole diameter of 6 mm and coupon width of 36 mm [26] and used as the benchmark to which to compare the tensile repair strength against.

2.3 Porosity characterization

For porosity evaluation of laminates and repair configurations, two complimentary methods were utilized: (1) X-ray tomography and (2) microscopy. Together these techniques allow for analysis of porosity size, shape and distribution. X-ray micro computed tomography (micro-CT) was conducted using a Yxlon Feinfocus Y.Fox 160.25 system on the carbon fibre laminate specimens with dimensions of 20 mm x 2 mm x 1.8 mm. X-ray analysis was undertaken at 46 kV (minimum voltage), 61 μA and 720 projections. The detector size is 1848 x 1480. The maximum system resolution is approximately 4 µm. For microscopy, polished cross-sections were imaged with an Olympus GX51 inverted metallurgical microscope. At least three images in various locations were analysed for each porosity value.

3 Results and Discussion

3.1 Porosity content

The volume and location of the individual porosities in the SVC and DVD manufactured laminates were analysed by X-ray micro-CT. The total averaged void fraction was established at 3.5 ± 0.3% for the SVC and 0.01 ± 0.01% for the DVD processed laminates at the given resolution. Fig. 2a shows the locations of the porosities as established from the 3D reconstruction of the X-ray CT slices. While individual carbon fibres were not resolved with this technique due to constraints of each pixel size in the 3D reconstruction, the alignment of voids with the plain weave pattern was clearly detected, indicating that a majority of voids were located in resin rich areas in the interstices between two yarns in warp and weft direction. This was further validated by the 2D cross-sectional top and side views.

Fig. 2b shows the distribution of porosities with respect to their volumes, where a significantly higher number of voids were detected at a size of $1\text{x}10^{-5}$ mm^3 and below. However, these 5,800 individual porosities accounted for only 2% of the total porosity in the laminate, which was not significant. Indeed, more focus should be placed on removing the fewer, but much larger porosities which contributed significantly to the porosity content located in the resin-rich gaps at the cross-over points of the two yarns in the plain weave material. In comparison, the DVD manufactured laminate showed only 27 individual small voids and was hence considered virtually void-free.

Fig. 3 shows the polished cross-sections of the SVC, DVD and autoclave manufactured laminates. Again, significant porosity content could be observed for the SVC laminates (Fig. 3a), with the averaged through-thickness porosity over all plies measured to be 3.0 ± 1.8%. This was in good agreement with the X-ray tomography results despite the obvious limitations of a 2D simplified analysis. Microscopy allowed for clear visualization of fibre bundles in relation to porosity distribution. Large spherical porosities (diameters up to 100-150 µm) accumulated in the resin-rich regions between the prepreg layers and around warp/weft cross-overs. Within the fibre bundles, smaller porosities with high aspect ratios aligned with the carbon fibres were found. Tserpes et al [27] reported similar results for autoclave panels cured at reduced pressure. As shown in Fig. 3b, the additional DVD pre-curing step resulted in an almost void-free laminate with negligible porosity of 0.2 ± 0.1%, and the process was therefore able to remove most solvent and volatiles. This is comparable to the autoclave cured laminate which is also void-free (Fig. 3c). Finally, no dry regions in between fibres were found in any specimens.

Preliminary tests showed that the porosity content was significantly higher in a repair scenario, where the additional effects of adhesive film and fully-cured parent material were present. To explore this phenomenon further, the 1D repair specimens were used to examine the effect of the adhesive film on the porosity. Fig. 4 shows the polished cross-sections of the 1D repair patches. The porosity in the SVC 1D repair patch increased to an average of 5.9 ± 0.5%, while similar porosity size and distribution characteristics were observed. In contrast, the DVD manufactured 1D repair patch did not show an increased amount of porosity content and was still considered void-free.

As scarf repairs introduce an angled patch geometry, the porosity content was analysed with consideration of the patch thickness. Fig. 5 shows typical through-thickness optical micrographs of the 2D repair toward the central location of the scarf, i.e. close to maximum patch thickness. The average porosity in the SVC 2D repair specimens at this location was typically similar to the 1D repair specimen with the adhesive film, with an average porosity of 7.6 ± 4.6% in the patch and 1.4 ± 0.4% in the adhesive being measured. Again, this was much higher than the porosity content of the laminate only cured specimens and highlights the importance of including the adhesive film for repair investigations. The porosity in the patch and adhesive is shown in Fig. 6 against the repair thickness (position along scarf line). Firstly, it can be seen that the porosity content in the patch is highest in the centre portion where the patch is the thickest. At this position we also observed significant adhesive film porosity. The porosity levels in the patch and adhesive tended to be lower towards the outer edges near the tip of the scarf (parts 1 and 6), due to the reduced patch thickness and more direct vacuum path. Secondly, the porosity content in both repair patch and adhesive film diminished if the DVD process was utilized, resulting in a mostly void-free repair. There was therefore no evidence of porosities caused by volatiles released from the film adhesive during the curing process. This finding is significant as it indicates that porosity-causing volatiles may travel from the patch region into the film adhesive and remain trapped as the film adhesive solidifies.

The typical porosity distribution in the thickness direction from the bottom or adhesive layer was compared in Fig. 7 for the SVC laminate patch and 2D repair. For all geometries, it was observed that porosity was generally highest around the centre of the patch as volatiles get trapped in this area. Significant variability in the porosity content in the thickness and lengthwise direction across the scarf porosity was observed for the 2D repair specimens, as shown in Fig. 6a and 7b. This would indicate that either initial volatile content or volatile flow is not uniform across the repair. Furthermore, we noted that the average porosity content increased with the addition of film adhesive and solid parent material into the curing configuration. It is postulated that an uneven porosity distribution will influence some material properties more than others as outlined in the next section.

Given that the DVD manufactured 1D and 2D repair specimens were essentially void-free, this would indicate that the increased average porosity levels in the 1D and 2D repair specimens - when compared to the laminate - should be attributed to the more limited volatile escape along existing vacuum paths. This effect is shown schematically in the Fig. 7 inserts. When curing the laminate geometry, volatiles can move along the vacuum paths through the thickness of the laminate and escape below or above the patch. For the 1D repair specimen the film adhesive alone seems to act as a barrier for volatile flow. For the 2D repair specimens the surrounding cured autoclave base and the film adhesive effectively seal off the lower vacuum path.

Our results for the 1D repair indicated that the film adhesive also played an important role in restricting volatile flow and entrapping gases. Fig. 8 shows the heat flow and viscosity data obtained from Differential Scanning Calorimetry (DSC) and rheology measurements. The DSC and rheology results clearly show the film adhesive curing at a faster rate than the prepreg. The onset cure temperature for the film adhesive was 100˚C, which was approximately 20˚C lower than for the prepreg material. Similarly, the film adhesive developed its modulus at a lower temperature of 120˚C compared to 150˚C for the prepreg. Therefore volatiles can only escape upwards through the repair patch following cure onset in the adhesive film. This leads to a larger amount of trapped volatiles within the adhesive film layer and patch due to the limited time available for volatile movement during the cure cycle. This explains the higher average porosity in the 1D repairs compared to the patch-only laminates.

Increased curing pressure is known to cause resin to flow out from between adjacent plies, thus reducing the size of resin-rich regions, with the direction of flow depending on the final part geometry [28]. For this work, the higher external curing pressure in the autoclave resulted in the most consistent laminate thicknesses as shown in Table 1. In comparison, the SVC laminates had the largest average thickness, which was attributed to lesser resin bleed-out and the presence of porosities. The DVD manufactured laminates had the lowest average laminate thickness compared to SVC and autoclaved laminates, which was caused by increased resin bleed-out from the additional pre-processing step, where a mass loss of 1.5% was typically observed. However, some regions of increased thickness could also be observed due to large resin-rich regions that were not seen in the autoclave laminates, contributing to the higher standard variation in thickness results. Next, the 1D repair laminate thicknesses were measured from polished cross-sections by not including the adhesive layer. The average thicknesses were lower than for the patch-only laminates due to the adhesive taking the place of the resin-rich surface layer. This is observable as adhesive is flowing through the first ply and is visible in some of the resin-rich regions between the first and second ply.

Fiber waviness was quantified by wave severity [29], calculated as the ratio of wave amplitude, δ, to the wave length, λ, and is summarized in Table 1. The high external pressure in autoclave curing ensures that the laminates have low fiber waviness. The pressure effect on fiber waviness can be compared against the SVC and DVD manufactured laminates, where the pressure applied is only at one atmosphere and fiber waviness was found to be significantly higher.

Lastly, it should be noted that the adhesive bondline thickness can also be significantly influenced by the curing process conditions and resulting porosity. Average bondline thicknesses of the different processes were measured. The scarf lap joints had the highest average adhesive thickness of 184±36 µm close to the nominal 200 µm with limited resin flow occurring through the edges of the specimens during cure. It can be seen that the bondline thicknesses for the soft patch repairs vary more than for the scarf lap joints. The SVC film thickness resulted in an intermediate thickness value of 160±53 µm, albeit with a large adhesive void content. The DVD 2D repairs had the lowest bondline thickness of 126±44 µm, which was attributed to the adhesive also flowing in the direction of the vacuum path through the prepreg thickness, effectively ‘bleeding’ into the soft patch. In fact, adhesive penetration was observed up to 1 ply (250 µm) above the adhesive layer. Adhesive porosity for the 2D DVD repair was minimal with less than 0.6%.

In summary, for all repair geometries and laminates investigated in this work, the additional B-staging during the DVD process allowed for efficient volatile removal from the prepreg material prior to cure, hence effectively eliminating the problem of porosity creation. As a result, void-free laminates and repairs were achieved, fulfilling stringent porosity requirements for aircraft repair of primary structures. However, this came at the cost of increased fibre waviness and reduced laminate and adhesive bondline thickness.

3.2 Mechanical properties of laminates and 1D repair specimens

The tensile, flexural and interlaminar properties of the laminates and 1D repair specimens consisting of 8 composite plies are summarized in Table 2. The presence of porosities up to 3% was shown to have no statistically significant effect on the tensile properties as the tensile modulus is a mostly fibre dominated property and the tensile strength is influenced by the fiber-matrix interface strength to facilitate stress transfer during progressive fiber fracture [30]. Similarly, the SVC and DVD manufactured laminates showed no decrease in tensile strength. It should also be noted that the tensile test method resulted in relatively large standard variations of up to 10% as results are additionally sensitive to the fiber alignment, the fiber volume fraction and end tab stress concentrations; hence potentially giving higher average strength results for lower quality panels as observed for the tensile strength of the SVC panel. The higher average porosity in the SVC 1D repair specimens showed a decrease in tensile strength of up to 22%, where high porosity content in the centre of the thickness can sufficiently reduce the stress transfer characteristics of the fibre/matrix interface. Eliminating the porosity effects by applying the DVD process improved the tensile strength to within 5% of the autoclave cured laminates. Finally, examination of the 1D repair fracture surfaces revealed no defects or delaminations that initiated from the adhesive layer which was observed to penetrate up to 1 ply.

The flexural modulus and strength appeared to be more sensitive than the tensile properties with regards to processing method. The higher porosity in the SVC laminates reduced the flexural strength by 12%. The DVD pre-curing removed the porosity, which increased the flexural strength by 7%, however this was still lower than the autoclave cured laminate due to fiber waviness effects which were considered more prevalent in bending than unidirectional loading as a result of higher strain and the presence of the stress gradient [31].

The interlaminar shear strength as determined by the short beam shear test was shown to be the most sensitive mechanical property for evaluating the influence of the porosity content [32] due to the (1) large spherical porosities in the resin-rich regions in between prepreg layers and (2) the porosity concentration towards the centre of the laminate as outlined previously. For the chosen lay-up, interlaminar shear stresses are expected to be highest at the centre of the laminate. Compared to the autoclave, the SVC laminates have a 15% lower interlaminar shear strength. In the 1D SVC repair, the interlaminar shear strength shows a further 8% decrease from the patch-only strength. This is caused by localized porosity contents of around 10% and 20% in the central plies and their resin-rich interlayers, respectively. The application of the DVD process was able to improve the interlaminar shear strength of the patch by 15% and 1D repair by 18%. The DVD manufactured laminates and 1D DVD repairs showed minor strength degradation in composite interlaminar shear strength compared to the autoclave process. Although both autoclave and DVD processes led to nominally void-free laminates without excessive bleeding, the larger fibre waviness and larger resin-rich areas for the DVD processes might account for the small reductions in interlaminar shear strength compared to the autoclave material.

3.3 Mechanical properties of 2D repair

A comparison of 2D repair and scarf lap joint tensile strength results is shown in Fig. 9. All laminates consist of 9 plies and therefore had a different thickness compared to the results presented in Section 3.2. As the thickness of the repair region was generally larger than that of the parent material and could vary locally due to adhesive film thickness, the thickness of the parent material was chosen for stress calculations to allow for direct comparison of joint, repair and parent material properties. For the given geometric configurations in Fig. 9, resulting stiffness values were all similar at 56 – 58 GPa and were hence not listed.

The upper limit of repair strength is defined by the laminate's autoclave tensile strength of 649 ± 36 MPa. For the lower limit, successful repairs have to exceed the design load of the structure, which are very conservative [6] and often based on notched allowable strengths such as the open-hole tensile strength [33]. The open-hole test resulted in a significantly reduced tensile strength of 293 ± 10 MPa. The decrease of 55% compared to the parent material indicates the typical mixture of notch-insensitive and sensitive failure behaviour given the local area reduction of 16.7% and estimated stress concentration factor of $K_T = 5.26$ for the given material and cross-ply lay-up [34,35].

The scarf lap joint tests showed a significant strength reduction of 22% compared to the autoclave tensile strength even for the relatively small angle of 2°. Based on previous research [19], it is understood that the zero plies within the outermost plies in the composite resulted in ply tip stress concentrations, hence triggering failure at the end of the overlap.

The 2D DVD repair showed a slight decrease in joint strength at 483 MPa compared to the scarf repair at 504 MPa, however there was some overlap of the error bars. This demonstrated that the low porosity in the DVD manufactured soft patch can restore the strength of a composite structure similar to a hard patch repair, while maintaining the flexibility of a soft patch repair. The DVD manufactured 2D repair specimen also showed significant strength improvements of 19% compared to SVC (407 MPa) for the given material and cross-ply lay-up. This was attributed to the significantly reduced porosity in the patch and bondline [36].

Brittle fracture in the form of sudden catastrophic failure and straight fracture surfaces was observed in both the scarf lap joint and 2D repair specimens. The scarf lap joint failure initiated at the end of the scarf, with some cohesive failure observed along the adhesive layer from the failure location prior to the crack propagating through-thickness into the parent material, as shown in Fig. 10a. Some specimens also show extensive delamination in the composite starting from the location of cohesive failure. For both types of 2D repair specimens, the crack propagates straight into the soft patch without any evidence of cohesive failure or delamination, as shown from the bottom view in Figs. 10b and 10c. It is likely that failure again initiated at the interface between the parent and patch at the tip of the scarf where the stress concentration is high [37]. The resin-rich regions along the adhesive bond line may have caused this difference in failure mechanism, but this effect is not significant in terms of the strength results as shown for the DVD process. The findings overall indicate that the effect of discontinuous fibres, ply tip stress concentrations as well as porosity were contributing and dominant factors for the resulting repair strength.

While actual repairs on composite structures are typically circular or oval in shape, rather than the straight scarf used on the 2D repairs, previous work has shown that 3D repair tensile tests have similar fracture mechanisms to the 2D repair tests [19]. The 2D scarf repair strength generally underestimated the load-carrying capacities of the 3D scarf repairs under tension due to the redistribution of stress in the hoop direction [38] and lower ply tip stress concentrations.

4 Conclusion

The manufacture of high quality, low porosity (<0.3%) composite repairs was demonstrated using a conventional autoclave cure prepreg material and double vacuum debulking (DVD) pre-curing. The SVC process in contrast had an averaged void content of up to 4.8% in the patch and 1.4% in the adhesive. X-ray micro-CT analysis showed that the larger porosities are of spherical nature and located in the resin-rich regions. These fewer, larger voids had a higher contribution to the overall porosity content. The experiments on the patch-only material showed a moderate averaged porosity of 3.0%. In a repair scenario, the presence of film adhesive and parent material restricts the vacuum path for volatile escape, which caused an increase in porosity to an average of 5.9%. However, the patch was observed to be essentially void-free when cured following DVD pre-curing even for the 1D and 2D repairs. The lower porosity in the DVD manufactured laminates generally allowed recovery of the strength lost compared to SVC. The lower porosity in the DVD manufactured repair resulted in a 19% increase in tensile repair strength for 2D scarf repair tensile tests over SVC repairs. Furthermore, the tensile strength of a DVD manufactured repair was similar to that of a scarf lap joint, demonstrating that the soft patch repair approach can achieve similar strength to hard patch repairs. We hence validated a low cost, viable pre-curing method that can be directly employed by industry to achieve high quality in-situ composite repairs.

There is substantial difference in static strength if the average porosity level exceeds standard industry allowable limits. The influences of other long-term factors, such as fatigue and moisture uptake during service of a repaired structure, are still relatively unknown [39] and are expected to also become critical with high porosity content.

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Tables

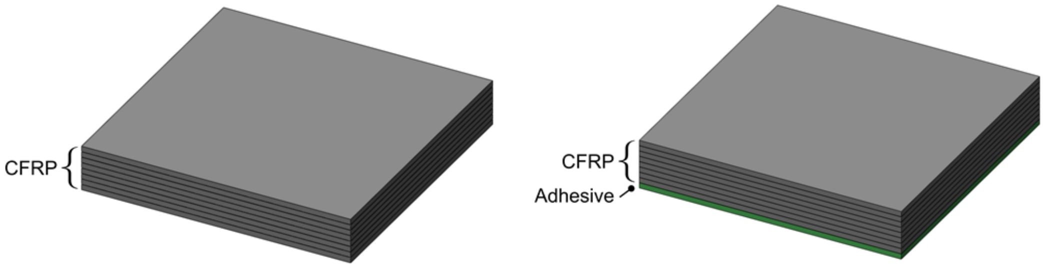
Table 1: Laminate thickness and waviness (8 ply)

Process		Laminate thickness (mm)	Fiber wave severity (%)
Patch-only	Autoclave	1.78 ± 0.01	3.10 ± 0.10
	SVC	1.82 ± 0.04	4.02 ± 0.55
	DVD	1.75 ± 0.03	4.46 ± 0.47
1D repair	SVC	1.74 ± 0.05	3.82 ± 0.18
	DVD	1.70 ± 0.02	5.12 ± 0.66

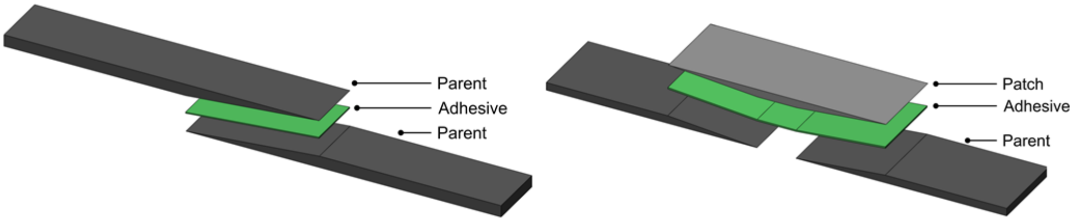
Table 2: Mechanical properties of patch and 1D repair laminates (8 ply)

Process		Porosity (%)	Tensile modulus (GPa)	Tensile strength (MPa)	Flexural modulus (GPa)	Flexural strength (MPa)	Interlaminar shear strength (MPa)
Patch-only	Autoclave	0.0 ± 0.0	57 ± 2	558 ± 46	59 ± 1	833 ± 29	72 ± 3
	SVC	3.0 ± 1.8	57 ± 3	574 ± 35	55 ± 2	735 ± 24	61 ± 2
	DVD	0.2 ± 0.1	57 ± 3	553 ± 33	57 ± 3	789 ± 32	70 ± 0
1D repair	SVC	5.9 ± 0.5	54 ± 1	437 ± 27	55 ± 2	743 ± 30	56 ± 2
	DVD	0.3 ± 0.1	58 ± 2	525 ± 13	54 ± 2	797 ± 26	66 ± 1

Fig. 1: Composite test and repair specimens



(a) Patch (b) 1D repair



(c) Scarf lap joint (d) 2D scarf repair

Fig. 2: X-ray micro-CT porosity analysis showing (a) porosity locations and (b) void counts and void fraction with respect to void size

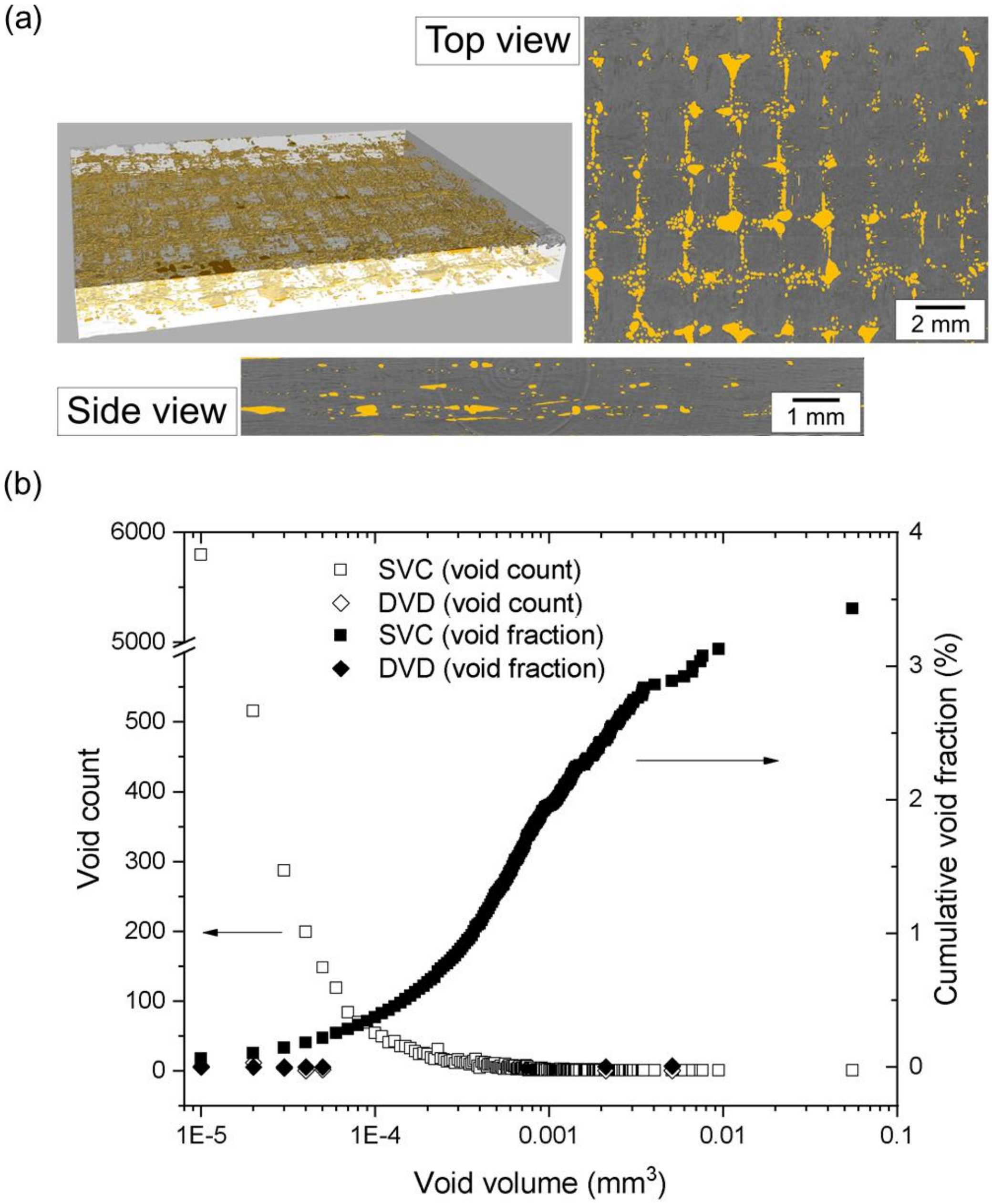


Fig. 3: Averaged through-thickness porosity evaluation of composite laminates with (a) SVC (3.0 ± 1.8%), (b) DVD (0.2 ± 0.1%) and (c) autoclave manufacture (void-free).

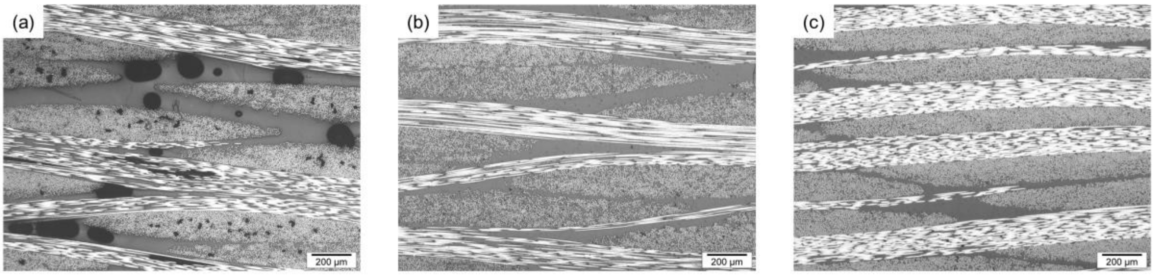


Fig. 4: Porosity evaluation of 1D repair patches for (a) SVC (5.9 ± 0.5%) and (b) DVD manufacture (0.3 ± 0.1%).

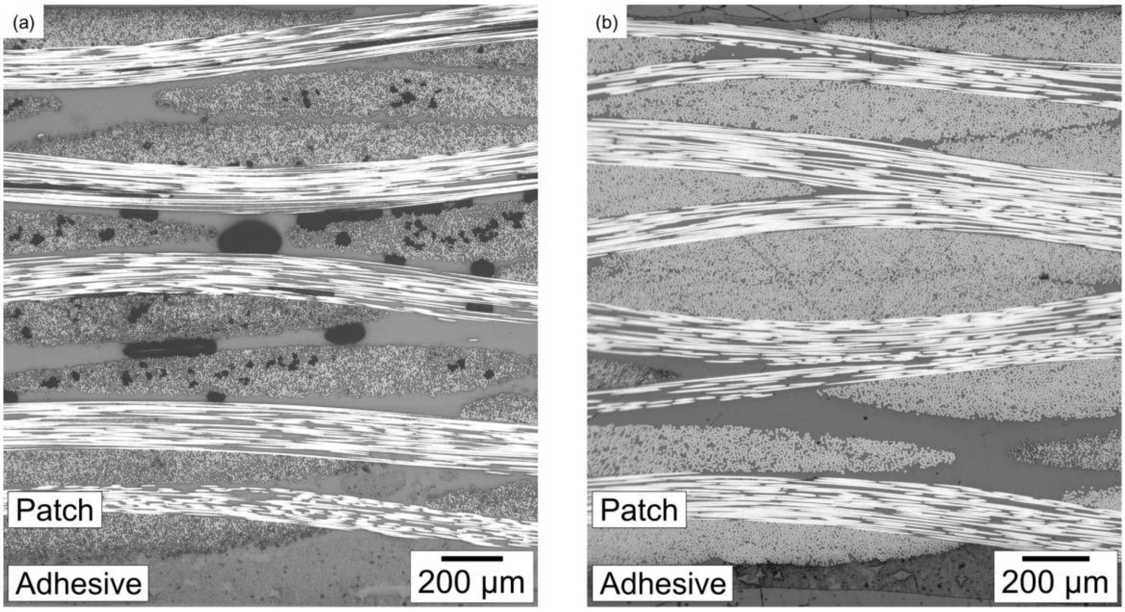


Fig. 5: Porosity evaluation of 2D scarf repairs for (a) SVC (7.7 ± 4.6%) and (b) DVD manufacture (0.1 ± 0.1%). Porosity content is averaged over patch thickness.

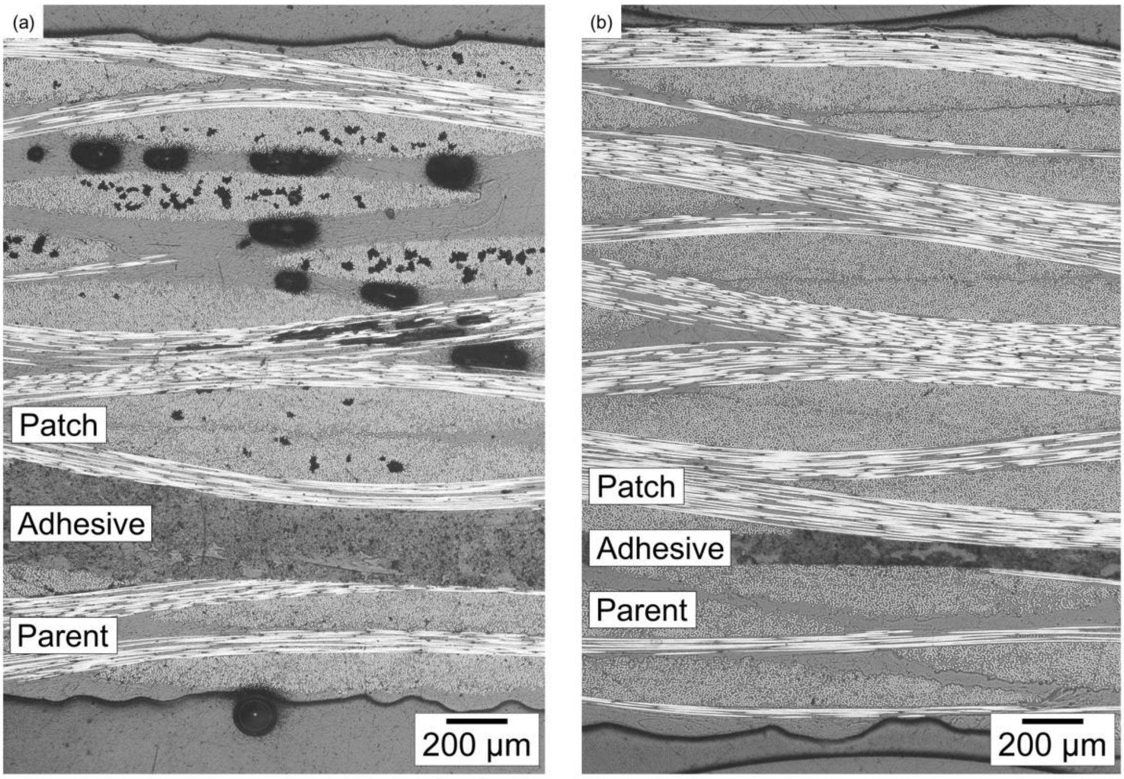


Fig. 6: (a) Patch and (b) adhesive porosity characteristics in 2D repair for SVC and DVD manufacturing.

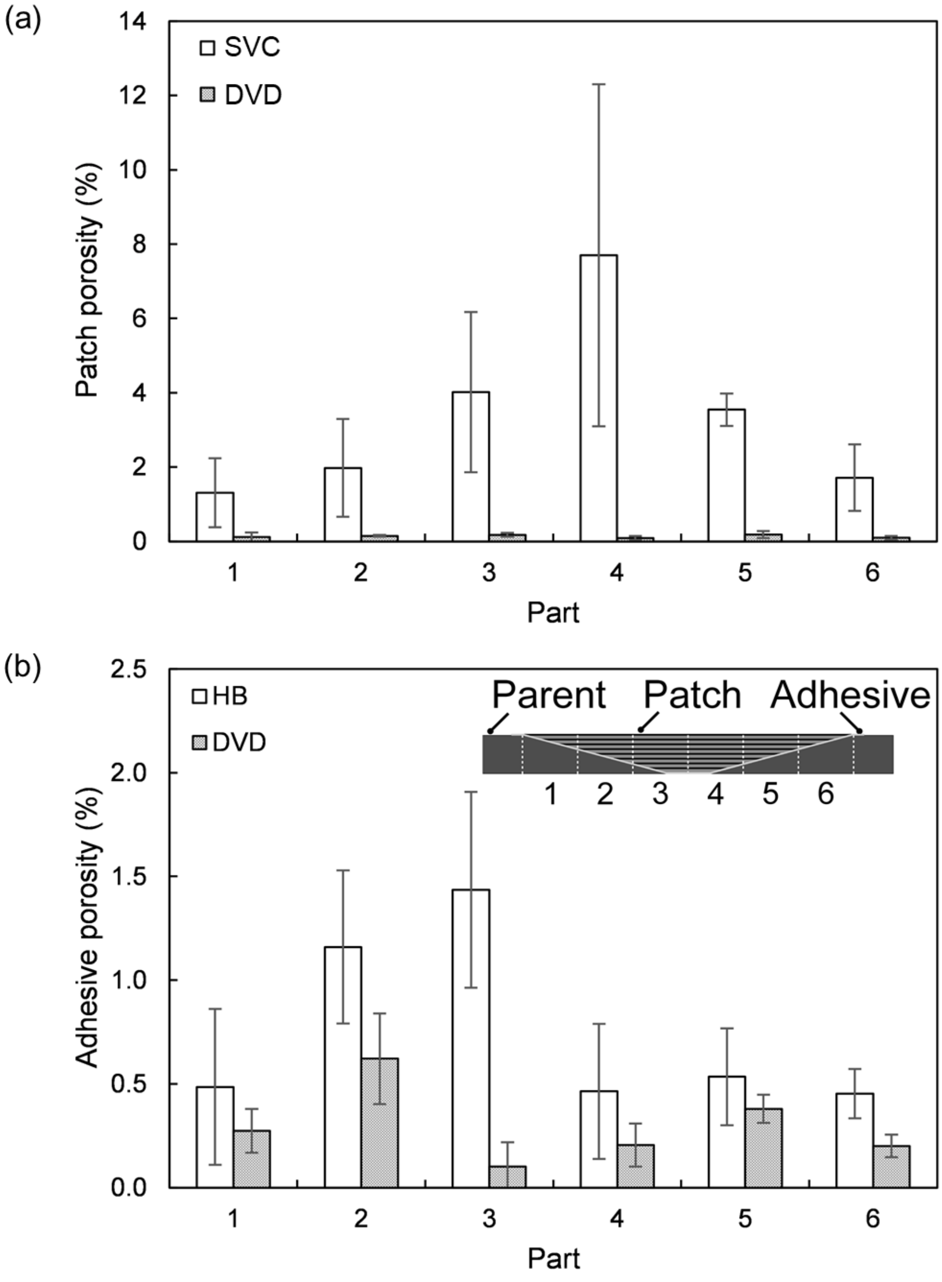


Fig. 7: Localised porosity analysis of (a) SVC laminate and (b) SVC 2D repair patch versus distance from bottom / adhesive layer.

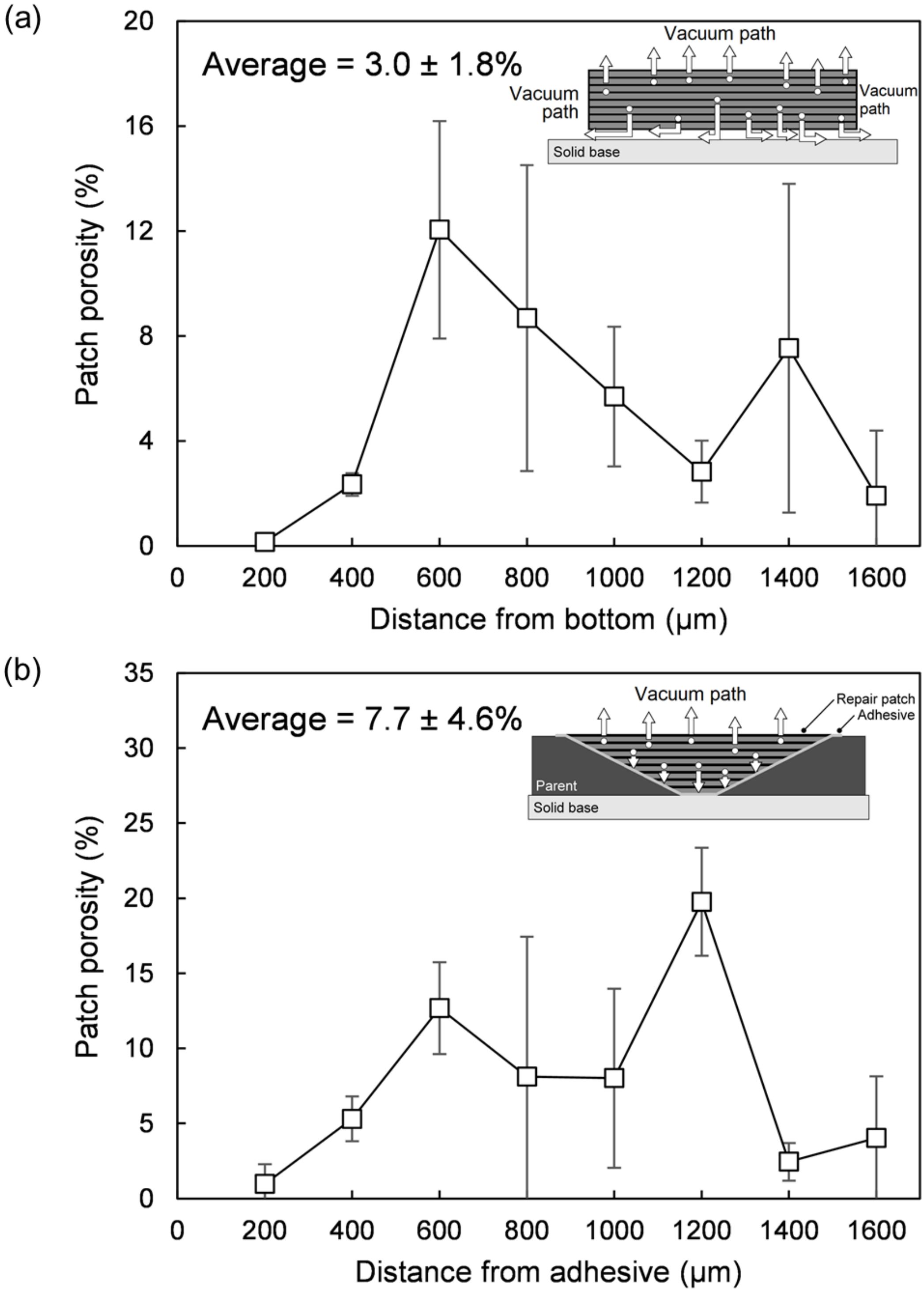


Fig. 8: Heat flow and viscosity of prepreg and adhesive with temperature

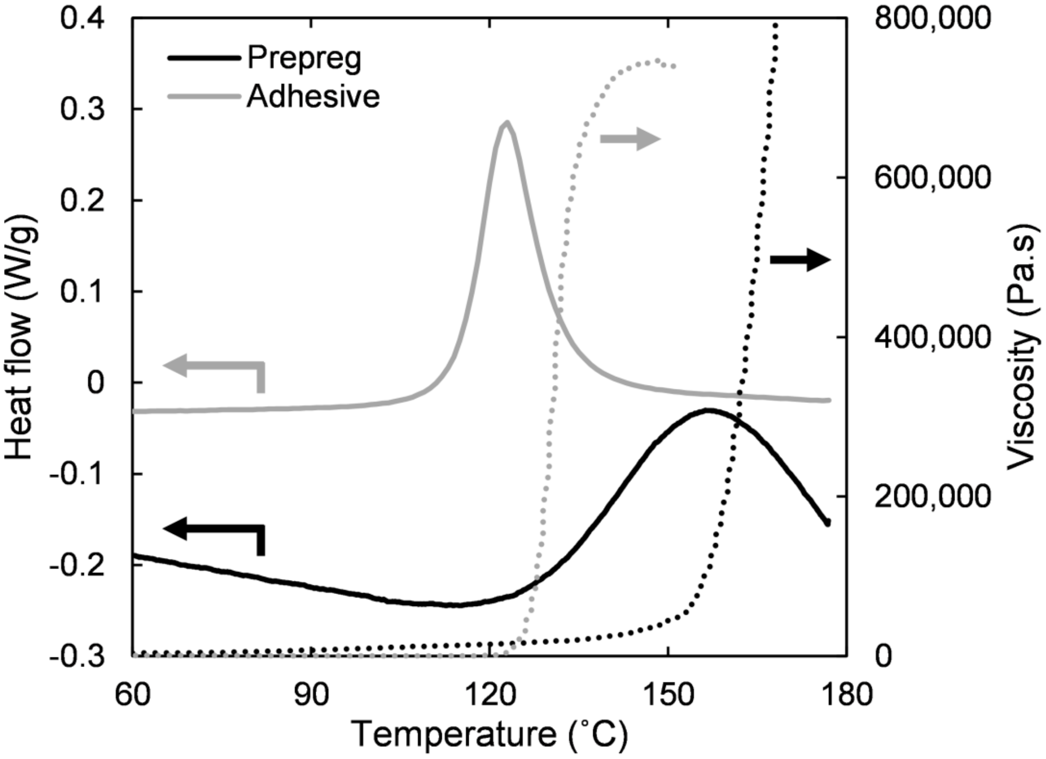


Fig. 9: Strength comparison of open-hole tension, 2D repair by SVC, 2D repair by DVD, scarf lap and parent. All laminates have 9 composite plies.

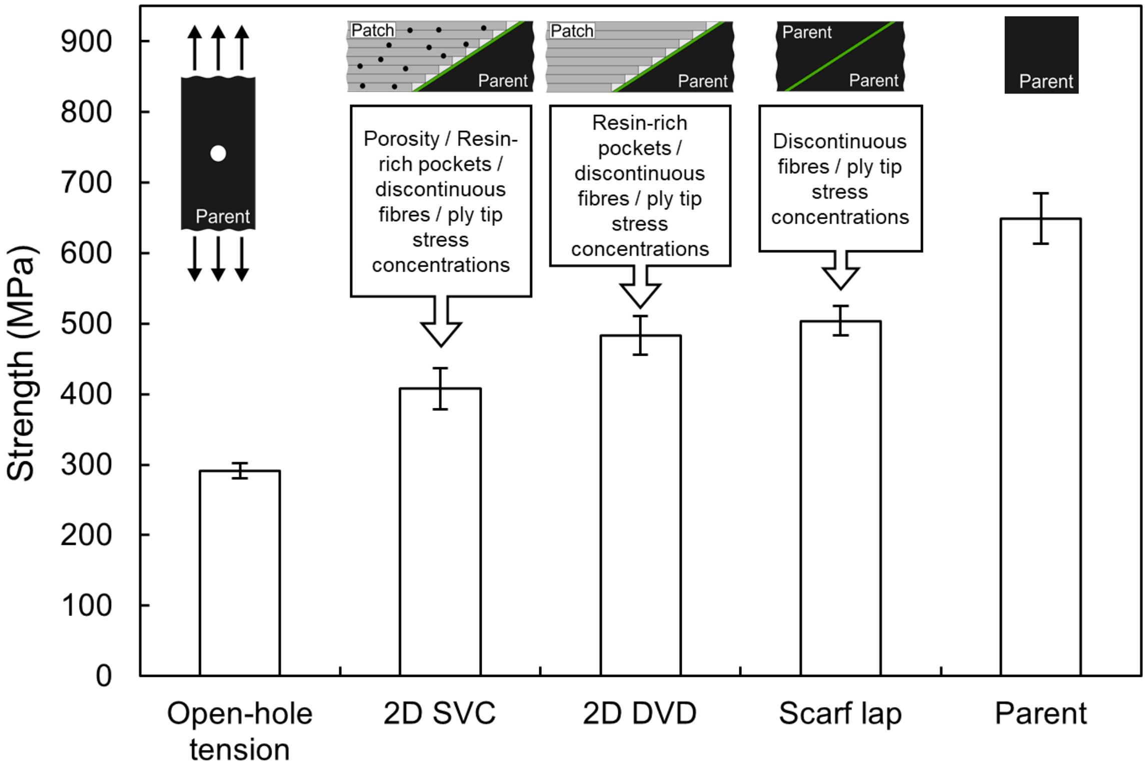


Fig. 10: Failure locations of scarf lap joints and 2D scarf repair

(a) Scarf lap joint

(b) 2D SVC repair

(c) 2D DVD repair