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INJECTION REPAIR OF COMPOSITES FOR AUTOMOTIVE AND AEROSPACE APPLICATIONS

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ABSTRACT

The continuous growth of composite materials for aerospace and automotive applications reinforces the need for efficient and effective repair procedures. Common bonded scarf or doubler repairs are well suited to critical structural applications, however they can be excessively demanding for lesser repair applications. Alternatively, previous research has shown low viscosity resin injection repairs to have considerable potential for the restoration of compressive strength in delaminated monolithic structures. This work extends such methods to the repair of dry spot defects in thick Carbon Fibre Reinforced Polymer (CFRP) laminates, and skin disbonds in Glass Fibre Reinforced Polymer (GFRP) / foam sandwich structures. Injection repairs have been conducted, under vacuum, using low viscosity room temperature curing epoxy resins, with minimal material removal and or surface preparation requirements. Infrared thermography has been used to validate the degree of resin infiltration for the repaired sandwich samples. Similarly, the large dry spot defects in CFRP laminates have been well filled, demonstrating a more rapid and reliable repair than current methods.

1 INTRODUCTION

Composites continue to be used for larger and more complex structures in both the automotive and aerospace industries. The Wrightbus New Routemaster for London and Bombardier C-Series aircraft contain prime examples of resin-infused composite structures for industry, designed and manufactured in Northern Ireland. The scale and highly-integrated state of such components makes them particularly costly and challenging to replace if they are damaged or incur manufacturing defects. Consequently, cost-effective repair procedures are imperative to both manufacturing and lifetime maintenance operations.

A range of approaches may be used for the repair of composite structures, depending not only on the structural performance and functionality, but also on the processing time, cost and labour requirements. Traditional mechanical fastening methods aim to quickly restore compressive strength and out-of-plane buckling but add stress concentrations at drill holes, and unnecessary weight. Alternatively, bonded patch repairs can be effective, but they influence the surface profile and often require extensive surface preparation. Adhesively bonded scarf repairs theoretically provide the most efficient restoration of strength, adding minimal weight and a negligible change to the surface profile. However such methods require considerable material removal and surface preparation, which can be prohibitively expensive, skill-dependent and time consuming overall. As a result, there is significant interest in rapid and minimally invasive injection repairs.

2 INJECTION REPAIRS

Resin injection repairs have previously been used for lightly loaded structures with small damage, delaminated monolithic structures and sandwiches with a face-sheet disbond. Typically, an inlet hole is drilled at the centre of the damage, and outlet holes are drilled at the damage periphery, before a low-viscosity resin is injected to flow through the delaminated area. Manual resin injection techniques are now fairly well established for the repair of composite delamination [1], however there is considerable room for improvement upon the basic guidelines [2]. These repair methods have the potential to minimise weight gain and material removal, whilst retaining aerodynamic efficiency. However, they remain limited to non-critical structural applications as they cannot effectively restore tensile strength [3].

2.1 Resins

The success of an injection repair relies on the selection of an appropriate resin, which has been well discussed in the literature [1, 4] and is primarily dependent on the viscosity and surface energy properties of the resin. Post-cure operational temperature limits, cure latency, fracture toughness and resistance to crack growth are also further considerations [5]. Generally, the most appropriate pre-polymer resins for injection repairs are epoxies, cyanoacrylates and cyanate esters. Figure 1 compares the thermal properties of these resin families against their recommended processing temperatures, at which viscosity is 0.15 Pa.s. In general, epoxies are the most popular adhesive due to their versatility and low cost, since they also exhibit good mechanical, adhesive and processing properties. However for high temperature applications cyanate esters often become preferable because of their superior thermal performance [6]. A new Bisphenol E Cyanate Ester (BECy) has recently gained popularity for injection repairs due to its unique properties of low viscosity at room temperature and high cured glass transition temperature [7], as seen in Figure 1. Cyanoacrylates have also seen some use in composite injection repairs, as their molecules are highly polar, resulting in facile and rapid polymerisation in the presence of water, metal impurities or anions. This, along with a low viscosity, makes them attractive for crack and delamination repair, however they are not suitable for cracks much larger than 0.15 mm or applications over 100°C [8].

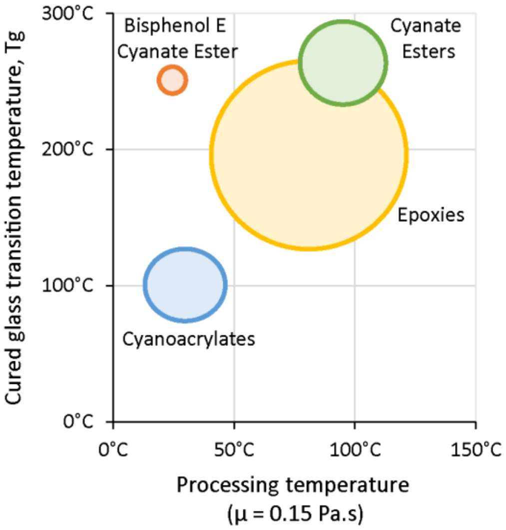

Figure 1: Relationship between processing temperature (at which viscosity is 0.15 Pa.s) and the cured resin glass transition temperature for various resin families [7].

2.2 Previous studies

Early research by Dehm and Wurzel investigated an epoxy resin injection repair of delamination in thin carbon fibre reinforced polymer (CFRP) composite panels subject to impact damage [9]. They drilled a 3.5 mm central hole to three-quarters of the depth of the laminate for the inlet, supported by a further four 1 mm diameter outlet holes around the periphery of the delamination area. The repair was conducted under vacuum and a 97% recovery of interlaminar shear strength was observed. A similar approach was undertaken by Russell et al. [4, 10], who developed their own epoxy resin to repair impact damage in 6.4 mm thick CFRP wing skins. In this case, Compression After Impact (CAI) testing showed an 85-100% recovery in the compressive strength of the repaired samples. More recently, Hautier et al. [11] and Moghe et al. [3] studied the injection repair of impacted quasi-isotropic CFRP composite laminates using epoxy resins, reporting 80% and 71-114% repair efficiencies respectively after CAI testing.

The use of Bisphenol E Cyanate Ester (BECy) resin for the injection repair of Bismaleimide/carbon fibre (BMI-CF) composites in high temperature applications has been investigated extensively by Thunga et al. [5]. Panels 6.35 mm thick with pre-existing holes were damaged via Hole Plate Shear (HPS) testing, repaired and subsequently tested in compression. They observed a complete recovery of compressive strength compared with the original drilled panels [12]. Pristine composite panels, without holes, have also been investigated using both static and impact loading to produce delamination. Subsequently, injection repairs were found to restore 70-100% of the compressive strength of the impacted panels and 90-125% of those damaged statically. Additionally, CAI testing of similar panels manufactured with different thicknesses revealed thinner samples, made from fewer plies, to have the greater strength recovery [6].

The Irish Centre for Composites Research (IComp) has also recently studied injection repair, publishing work using cyanoacrylate adhesives to repair impact damage in CFRP composites [13]. A range of different strength tests were explored, among which CAI testing showed a repair efficiency of 92% and four-point bending showed a complete strength recovery [13].

Table 1 compares the CAI results from a range of injection repair literature over the last 30 years. In each case the desired delamination size ranged from 25-80 mm in diameter and was repaired using a configuration of drill holes; commonly a single inlet at the centre of the damage and multiple outlets around the periphery of the detected delamination damage. Several of these studies also reported a failure to restore the tensile strength of injection repaired panels [3, 13], as fibre breakage could not be repaired.

Study		Panels		Resin		CAI repair efficiency
Year	Author	Material	Thickness	Type	Viscosity	
1989	Dehm et al. [9]	CFRP	2.45 mm	Epoxy (Rutapox CY160N/SL)	0.06 Pa.s (40°C)	97%
1992	Russell et al. [4]	CFRP	6.4 mm	Epoxy (undisclosed)	0.65 Pa.s (25°C)	85-100%
2010	Hautier et al. [11]	CFRP	-	Epoxy (RTM6)	0.19 Pa.s (80°C)	80%
2014	Thunga et al. [6]	BMI-CF	3 mm	BECy (EX 1510/B)	0.15 Pa.s (25°C)	100%
			4 mm			70-85%
2015	Moghe et al. [3]	CFRP	4 mm	Epoxy (Araldite GY257)	0.5-1 Pa.s (25°C)	71-114%
2015	Slattery et al. [13]	CFRP	4 mm	Cyanoacrylate (Loctite 406)	0.02 Pa.s (25°C)	92%

Table 1: Comparison of previous injection repair studies.

2.3 Industrial applications

Much of the previous research has focussed on the injection repair of impact damage in relatively thin monolithic composite panels for the restoration of compressive strength, however this work investigates the use of injection repairs for two specific industrial applications: the re-bonding of glass fibre reinforced polymer (GFRP) sandwich skins to foam core material, and the filling of dry spots in thick monolithic CFRP laminates. For both applications, there was a significant opportunity to develop a faster method that added minimal complexity to the repair process. All of the following work is for validation of process for a repair methodology that wholly falls within the scope of patent defined in reference [14].

3 REPAIRING GFRP/FOAM SANDWICH DELAMINATION

3.1 Problem definition

In order to achieve considerable weight savings, the rear section of the Wrightbus New Routemaster for London has been developed primarily from several large composite structures. These are made from a complex combination of monolithic woven GFRP and GFRP/foam sandwich regions. In operation, these structures are frequently subjected to impact damage, resulting in face-sheet delamination. Currently, such damage is repaired by first removing the damaged areas of the structure; then sanding, scarfing and patching the defective region via *in-situ* wet layup, often under vacuum. This can be particularly labour intensive and wasteful, especially in the case of a disbond where the outer skin remains in good condition. Hence, an alternative repair that can more rapidly restore the structural integrity is desirable, and injection repair was identified as a potential solution.

3.2 Sample preparation

Sandwich samples, 150 × 100 × 18 mm, were manufactured from woven GFRP pre-preg and foam core material. Impact testing with a standard test machine was found to be incapable of reproducing realistic delamination damage. Hence, artificial disbonds were created by first removing an outer skin from each sample and then partially re-bonding it to the foam core by applying epoxy resin only around the perimeter of the desired delamination region. Using this approach, disbond areas larger than 80 × 60 mm were consistently created, and were verified using Non-Destructive Inspection (NDI) techniques. Infrared thermography was found to be the most effective NDI method to determine the actual size and location of each defect, as ultrasonic techniques were found to be ineffective for these materials.

3.3 Repair method

Based on the size and location of delamination in each sample, a pattern of evenly-spaced 1.5 mm diameter holes were drilled through the outer skin; ensuring that outlet holes were a maximum of 30 mm from the nearest inlet across the whole delamination area. After drilling, separate strips of peel ply were placed over the inlet and outlet holes with sufficient space to then apply sealant tape between the inlet and outlet regions. Breather cloth was wrapped around the samples and over the outlet regions, connected to a vacuum port away from the sample itself. This was then encased in a vacuum bag as shown in Figure 2, and checked for any leaks. Low viscosity epoxy resin was then inlet into the delaminated samples at room temperature.

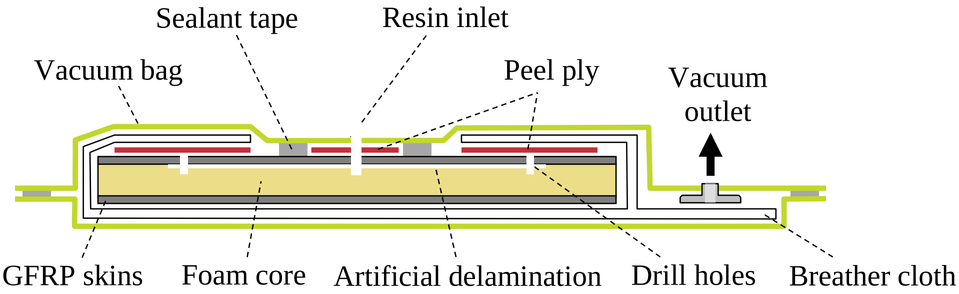

Figure 2: Injection repair bagging approach for the delaminated GFRP/foam sandwich samples.

3.4 Results

Visual observation generally provided a good indication of the success of each infusion, where resin could be seen at the outlet holes after having clearly travelled through the interior delamination region. This is shown for a sandwich sample containing a 90 × 60 mm delamination area, with three inlet and eight outlet holes, in Figure 3. Further inspection via NDI was used to confirm the interior filling, as seen in Figure 4. With only some small areas that remained quite dark in the thermographic images, suggesting that they may not have been filled completely.

Figure 3: Repaired GFRP/foam sandwich sample.

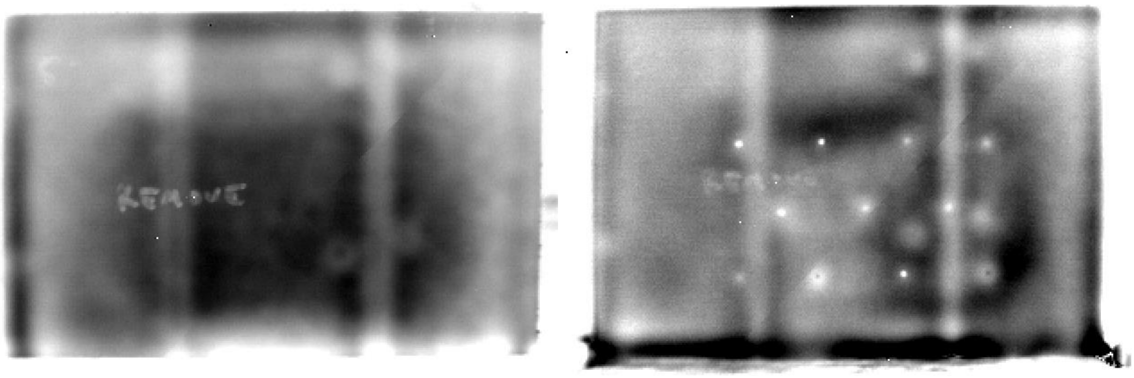

Figure 4: Infrared thermography of a sandwich sample before and after injection repair.

4 REPAIRING MONOLITHIC CFRP DRY SPOTS

4.1 Problem definition

During the manufacture of large composite structures, processing issues can result in 'dry spots'; where the reinforcing fibres are not wetted, or are only partially wetted, by the resin. Such defects are particularly problematic for aerospace applications, as from a structural certification perspective, they must be considered as holes through the complete thickness of the part. Even in non-structural areas, these defects are problematic as they allow for moisture ingress, further damage propagation and also hinder surface coating/painting efforts. Currently, the repair procedure for such defects is often limited to the outermost plies and is purely cosmetic, in spite of considerable labour requirements. However this remains preferable to complete part replacement. Evidently, there is a strong need for structural or at least more efficient and effective cosmetic repair methods.

4.2 Sample preparation

A large defective CFRP panel (720 × 945 × 10.4 mm) was provided for the purposes of this investigation to develop an improved repair method. The panel contained an extensive defective region, roughly conical in shape, with a very shallow taper and completely dry fibres in the centre. Towards the edges of the dry spot, fibres were well wetted with some voids remaining on the surface between the woven tows. However the panel also generally exhibited more porosity than would be acceptable for production parts, as a result of its manufacturing process. Visual inspection and tap testing were conducted in order to categorise the extent of the main defects in the panel and to inform decisions on sample preparation. From these observations, a range of dryness was defined:

- Very dry fibres: The top layers of the composite felt completely dry, with a dull appearance. Layers can be physically pulled out-of-plane by several millimetres.
- Dry fibres: Surface fibres seemed completely dry, also quite dull in appearance, and tows showed some movement when probed.
- Moderately dry fibres: A mixed zone where surface fibres were mostly dry, able to be moved but tows remained fixed in place.
- Some surface porosity: Regular gaps of porosity between fibre tows, although the tows themselves remained wetted, reflective and immovable.
- Near pristine: Laminate was mostly smooth and reflective, with only some minor defects between tows.

Subsequently, a series of six samples were cut across the full width of the defective panel, spanning the transition from dry to pristine regions, as shown in Figure 5. After sectioning, each sample was wiped clean using solvent and cloth, then the edges were inspected to measure the depth of dryness throughout the panel. Figure 6 shows the extent of the dryness in the cross-section of the ‘dry fibre’ region, where the top plies are completely dry and easily separate from the laminate. In the worst affected region of the panel, the maximum depth of the defect was found to be more than 25% of the panel thickness, at 2.8 mm deep.

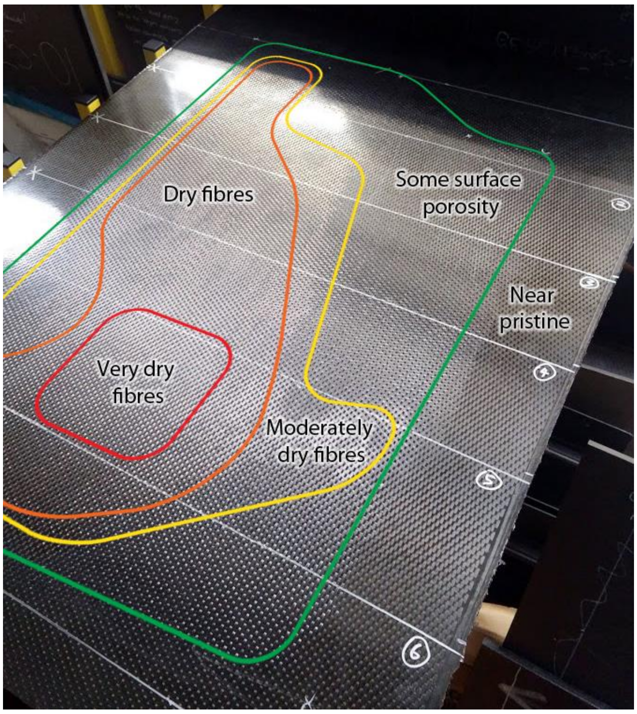

Figure 5: Categorisation of dryness and sectioning of the defective panel.

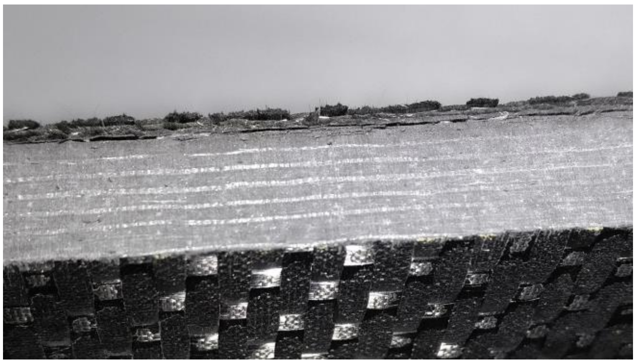

Figure 6: Panel cross-section in the 'dry fibre' region.

4.3 Repair method

The approach for these repair trials was based on a combination of resin infusion and injection repair, conducted under constant vacuum. Since only a small volume of resin was required to fill the dry regions and surface porosity, a simplified inlet configuration was used compared with typical reservoir and inlet port configurations used for infusion. Furthermore, unlike common resin injection methods, where drilling is required in order to network the damage area, no drilling was necessary as the dry region was inherently well networked.

Vacuum bagging of the injection repair samples was complicated by the open cuts across the dry defect regions, meaning that the two long edges needed to be sealed inside the enveloping bag. Otherwise, a similar bagging arrangement with wrapped breather cloth from Figure 2 was used for the CFRP repairs. Outlet vacuum ports were placed at the pristine ends of the samples, and once bagged, the inlet configuration was established over the driest region of each sample, prior to resin injection.

4.4 Results

Three similar samples with moderately large dry fibre regions (identified as samples ‘6’, ‘3’ and ‘4’) were repaired and evaluated using a range of visual, non-destructive and microscopic inspection techniques. Visual inspection revealed that the worst dry fibre regions of the defective panels had been successfully filled, although the larger areas of surface porosity did not completely fill in all cases. Repositioning of the inlet location, flow-enhancing media or a heated repair environment would likely resolve this issue. The repaired surfaces of samples ‘6’ and ‘3’ are shown in Figure 7 and Figure 8 respectively. A small section was cut away from the repaired edge region of sample ‘6’ for subsequent microscopy, seen in Figure 9. Here the top plies from the repaired region appear to have been well wetted and filled with resin as a result of the injection repair process, exhibiting no voids. However, considerable porosity appears to have also been introduced through the full thickness of the laminate as a by-product of the defect’s manufacture.

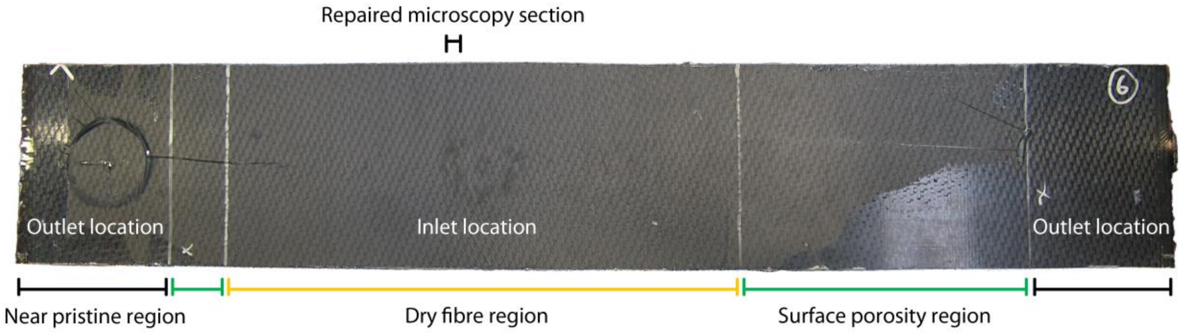

Figure 7: Injection-repaired top surface of sample ‘6’, highlighting the cross-section used for microscopy.

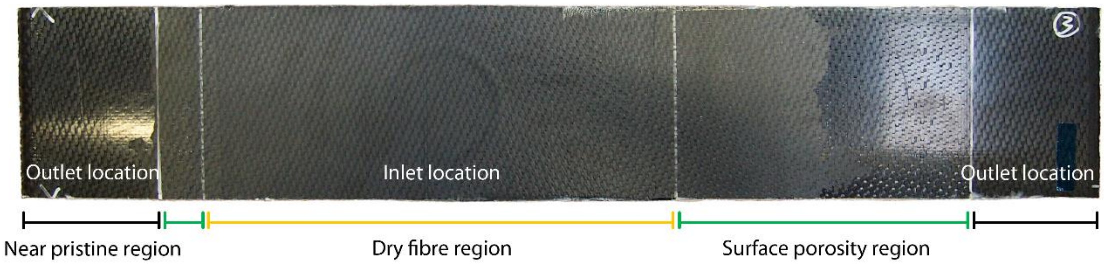

Figure 8: Injection-repaired top surface of sample ‘3’.

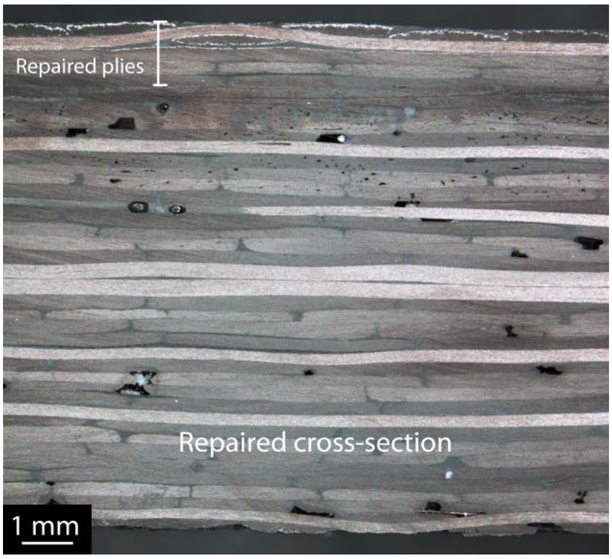

Figure 9: Microscopic cross-section from repaired edge of sample '6' (as depicted in Figure 7).

Ultrasonic inspection conducted before and after the injection repair of sample '4' was unable to distinguish the benefits of the repair from the considerable porosity that existed through the thickness of the laminate in the repair region. Unfortunately this porosity was the result of artificially manufacturing dry spot defects, however in reality such porosity would not be acceptable for a production part. Hence, it is expected that this injection repair approach could be better validated by ultrasonic inspection for real dry spot repair applications that aren't coupled with such extensive porosity.

5 CONCLUSIONS

Although composite repair methods have been widely studied, there are still significant opportunities for less invasive, more effective and more rapid repairs. Compared with traditional material removal and patching methods, injection methods are seen to be advantageous for the repair of delamination damage and dry spot defects. Previous research has extensively studied the potential of such delamination repairs in moderately thick monolithic structures, particularly for the recovery of compressive strength, however these methods are still not widely used in industry.

This research demonstrates similar injection repair trials for both delamination in GFRP/foam core sandwich structures and dry spot defects in thick CFRP laminates, for automotive and aerospace applications respectively. In both cases, the repairs were minimally invasive and required only vacuum bagging along with low viscosity, room temperature curing resins. Infrared thermography was used to confirm the resin infiltration in GFRP/foam sandwich samples. The combined injection/infusion approach for repairing dry spot defects in CFRP structures also showed good filling as a cosmetic repair, with aims for future mechanical testing to classify the method for structural repairs.

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