DEVELOPMENT OF ROBUST REPAIR PROTOCOLS FOR COMPOSITE AIRCRAFT STRUCTURES

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ABSTRACT

While in service, aerospace components with intensive use of carbon-fibre-reinforced thermoset polymers experience damage requiring repair. Co-bonded scarf repairs provide excellent strength recovery for composite skins; however, the repair environment can make their processing a challenge. In particular, the available consolidation pressure is limited to atmospheric pressure, and typically leads to repairs with high void contents. The presence of pre-bond moisture may also negatively affect the quality of bonded repairs and their resulting strength, inspection, and durability. In this work, two strategies for co-bonded repairs were developed in a laboratory scale environment. First, the use of Vacuum Bag Only prepregs, referred to as "semipregs" in reference to their partially impregnated tows, were investigated. Second, a wet layup repair approach was studied as this is another solution used when storage of prepreg material is not convenient. A new air evacuation strategy was successfully developed for prepreg patch repairs with the introduction of air breathable adhesive film. For wet patch repairs, the optimum impregnation and processing conditions were found. These laboratory-scale findings were applied to repair a decommissioned A320 elevator. This exercise illustrated the challenges of applying solutions developed in controlled conditions to real structures. Nevertheless, the protocols developed significantly improved repair quality and robustness.

1 INTRODUCTION

Until recently, the use of composite materials in aircraft was limited to flaps, ailerons, engine nacelles, fairings, and other secondary structures, and the repair of these composite structures had been of relatively minor concern [1]. Since the commercialization of the Boeing 787, with entire pressurized fuselages and wing structures made of carbon-fibre reinforced polymer composites, traditional aluminum alloys are being replaced by composite materials for primary structures. Damage inevitably occurs while in service. In-flight hail, bird, or lightning strikes [2] may cause critical damage, but actually impact damage from ground service vehicle bumps or runway debris is found to represent over half of all damage on the A320 family [3]. When detected damage exceeds the Allowable Damage Limit (ADL) size, a structural repair is needed to restore the load-carrying capability, and repair operators follow the instructions of the Structural Repair Manual (SRM) provided by the Original Equipment Manufacturer (OEM) [4]. Hence, there is a growing need for improved design, analysis and processing methods to extend the scope, efficiency, performance, and durability of composite repairs [5].

To repair damaged structural components, two main methods are typically considered: bolted repairs and bonded repairs [6]. Bolted repairs, relying on mechanical fasteners, significantly increase the weight of the component. On the other hand, by joining a patch to the parent structure by means of an adhesive, bonded repairs present significant advantages over bolted assemblies. Foremost, the stiffness and strength recovery obtained with bonded scarf repairs are close to the original structure. More uniform load transfers, low-weight and aerodynamic smoothness are also achieved with bonded repairs [7]. While being a desirable method, adhesive bonding is currently difficult to certify, and aircraft Structural Repair Manuals (SRM) mainly rely on structural bolted repairs for repairing load-bearing structures. As of now, bonded repairs are essentially cosmetic, considering that the repair does not carry any load, since there is no Non-Destructive Evaluation (NDE) method to assess the strength of a bonded repair

[8]. The lack of understanding of materials, processing and quality relationships in adhesive bonding is also another major concern highlighted by a recent Report from the US Government Accountability Office [9] and several authors [1, 6, 10, 11].

The common technique for bonded repair is referred as the soft patch approach. This method implies laying-up a repair patch into the scarf cavity by matching the ply configuration of the parent component. Both patch and adhesive are cured at the same time. In prepreg based repairs, the bondline is formed by an adhesive film, while in wet patch repair the potting resin is normally used to fulfil the task of the adhesive. In the same way that composite components are highly dependent on their processing, the quality and the resultant performance of composite bonded repairs are also affected by the manufacturing process. After inspection of the damage area, co-bonded repairs of components involve a series of steps: removal of the damaged plies, scarf of the parent structure, surface preparation, adhesive and un-cured patch plies layup, pressure and heat application to consolidate and cure the repair materials, post-repair inspection, and refinishing. If the repair process is inadequate, poor patch consolidation can lead to patch wrinkles, bondline thickness variations, voids, and disbonds [12].

The objective of this work is to optimize both prepreg and wet patch repair processes in order to minimize voids in the bondline and maximize the patch strength recovery. Figure 1 illustrates the approach used to develop robust processing protocols for both prepreg and wet patch repairs. Material characterization involved the development of thermochemical and rheological models of the resins and adhesives used in this research. Laboratory scale controlled experiments were used to optimize a breathable adhesive film and fibre preform impregnation method for the prepreg and wet patch respectively. Finally, the repair protocols were tested on a ~14-year-old aircraft component where the repair process was monitored and the quality of the repairs was assessed by non-destructive and destructive tests.

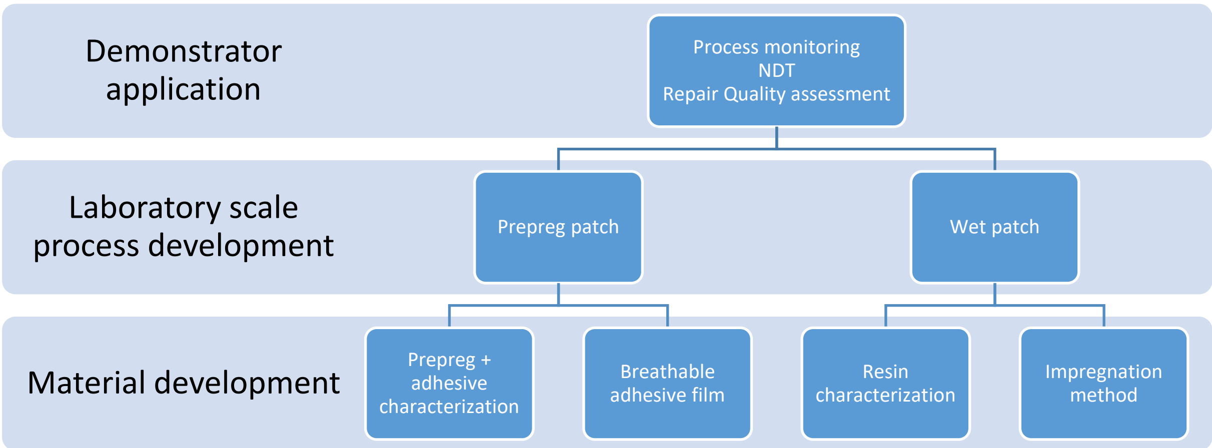


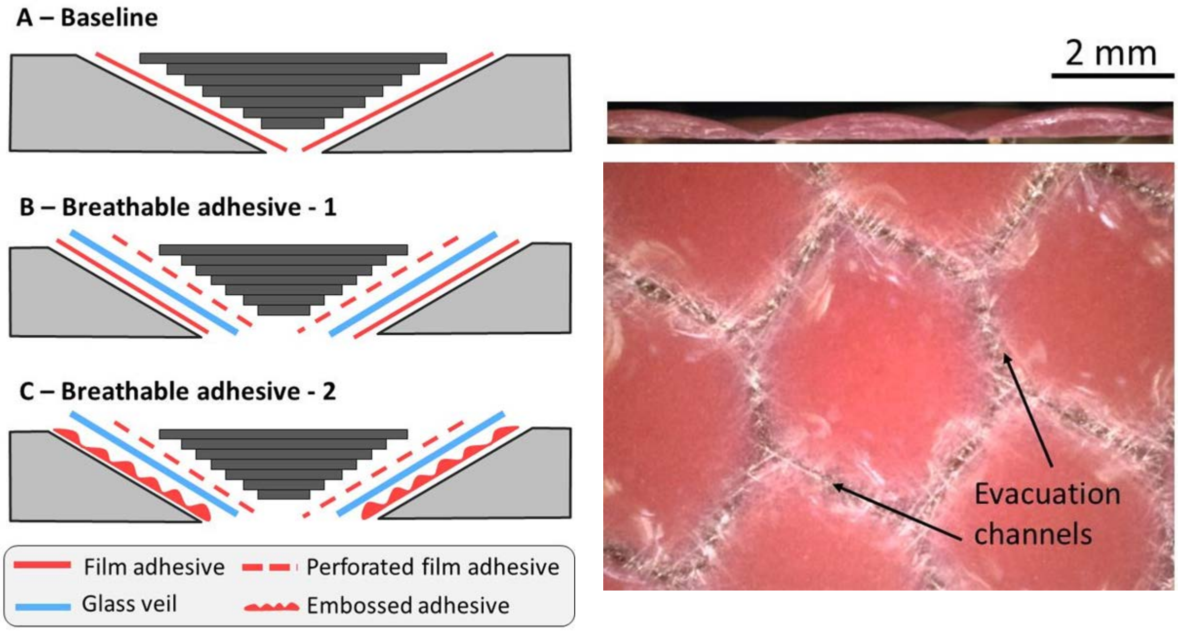
Figure 1: Task organization for the development of robust quality repair processes.

2 LABORATORY SCALE REPAIR PROCESS DEVELOPMENT

Two repair schemes were investigated in this work. Laboratory scale process development for prepreg and wet patch repairs was conducted in controlled laboratory environments. Special fixtures were designed in order to simulate repair process conditions and allow for process monitoring.

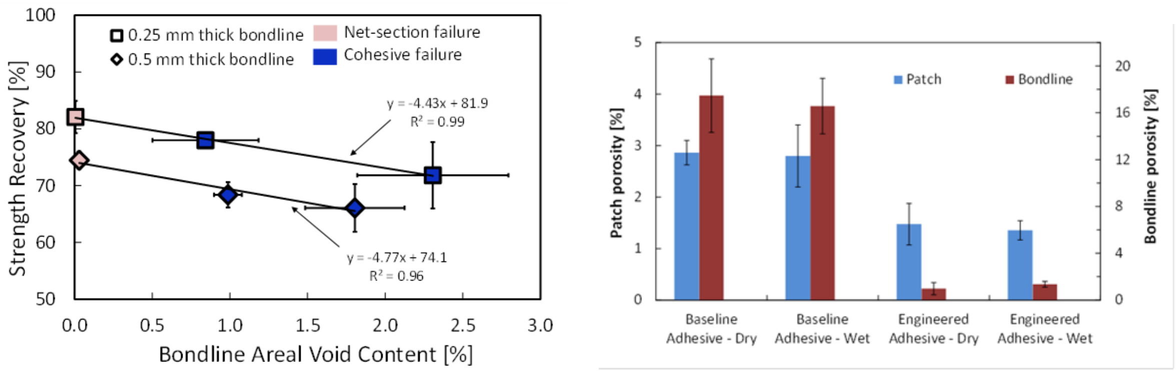
2.1 Prepreg patch repair

Repairs used a similar quasi-isotropic layup as the parent laminates. To overcome the lack of transverse air evacuation capability of the prepreg plies, two in-plane breathing strategies were implemented and compared as illustrated in Figure 2a). Configuration A is the baseline repair arrangement, in which the adhesive film and repair plies were laid up in the repair scarf cavity. For configuration B, a fine dry glass veil was sandwiched between pieces of adhesive film, with the adhesive adjacent the patch perforated by means of a porcupine roller. For configuration C, in addition to perforations, the second adhesive film was textured to provide larger pathways for air within the adhesive films and the repair plies as shown in Figure 2b). The results showed that entrapped-air induced voids in a repair can be mitigated even with a vacuum bag only process [13]. The void content results indicated that the presence of air evacuation channels within the adhesive film improved bondline quality and patch consolidation. When using an embossed adhesive film, in-plane air evacuation of the repair prepreg plies was possible, and patch intra-tow micro-porosity was largely eliminated. The bondlines, within which most of the load is transferred, were also found quasi void-free when a textured adhesive film was used. The results in Figure 3a) show that repairs with void-free bondlines have the highest strength recovery at 82 ± 3 % and 74 ± 2 %, for 0.25 mm and 0.5 mm thick bondlines respectively. Figure 3b) summarizes the average bondline and patch voidage found in co-bonded repairs of Nomex sandwich panels with semi-impregnated prepreg repair plies under vacuum-bag only pressure [14]. The use of an 'air breathable' adhesive film significantly reduced the average void content in the patch (from 2.8 % to 1.5 %) and in the adhesive (from 17.0 % to 1.2 %). Whether the parent panel was fully dry or partly wet did not significantly change the adhesive or patch porosity in the performed trials.



a) b)

Figure 2: a) Schematics of repair air evacuation strategies: baseline (A), non-woven dry glass veil interleaved between a perforated and baseline adhesive film (B), and another breathable adhesive strategy in which an adhesive film is embossed (C). b) Close-up photographs of the embossed adhesive film: cross-sectional view (top) and in-plane view (bottom). Air evacuation channels are created by hexagonal core cell imprints, revealing the non-woven polyester carrier in the film channels.

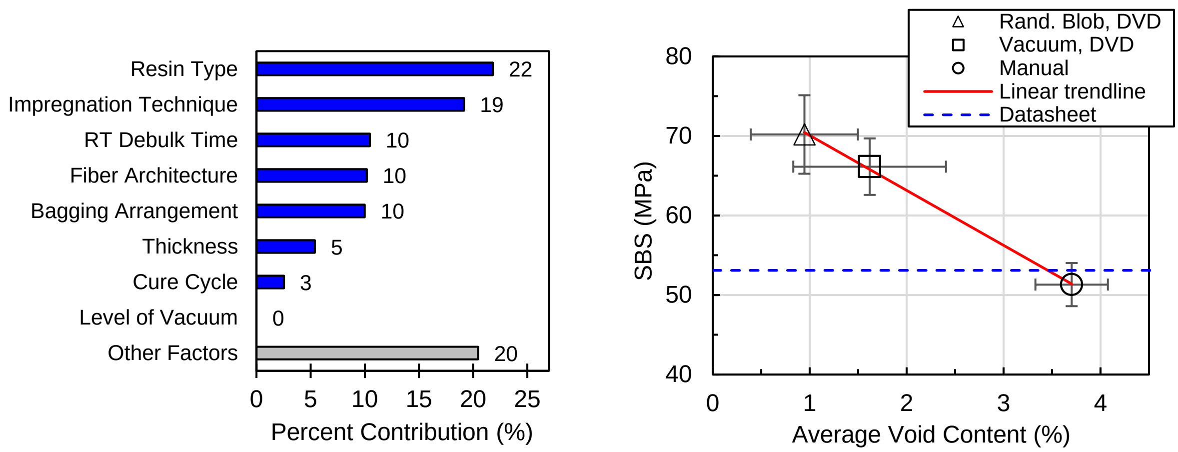


a) b)

Figure 3: a) Bonded scarf repair tensile strength recovery as a function of bondline void content for two bondline thicknesses (3 ° scarf angle). Observed failure modes, either net-section or cohesive, are indicated for each repair group by the colour code. b) Average and standard deviation of measured void content in repair patch and bondline for sandwich panel cross sections.

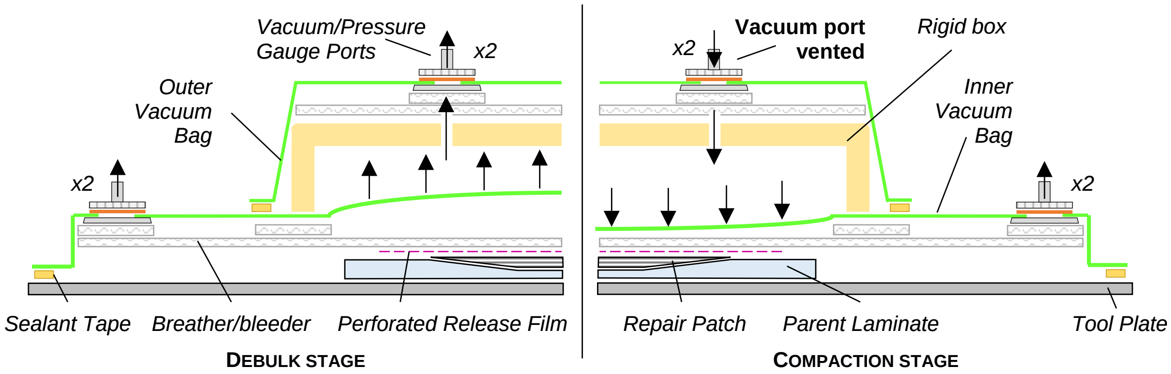
2.2 Wet patch repair

To investigate the quality within wet layup repair patches, patches were manufactured on a monolithic parent structure. The following parameters were investigated: resin type, impregnation technique, bagging arrangement, debulk time, fibre architecture, repair thickness, level of vacuum and cure cycle. An L18 Taguchi orthogonal array was used to select a small number of patch configurations to manufacture [15]. An average repair patch void content of 6.3 % was measured for the 18 different wet layup patches considered. While resin type was predicted to be the most important factor for porosity with a 23 % contribution, this variable also determined the cure temperature (Figure 4a)) as resins with different cure temperatures were used. Consequently, cure cycle dependent effects on the resin viscosity and volatile pressure contributed to the importance of this factor. The resin impregnation technique was almost as significant as the resin type, with the vacuum impregnation method [16] leading to the lowest porosity. The Double Vacuum Debulk (DVD) bagging arrangement (Figure 5a)) proved best overall for patch quality, though it would present a challenge for curved parts as implemented. Also, vacuum as low as 50 kPa did not result in higher porosity. Figure 4b) shows that the optimization of the wet patch process led to an increase in Short Beam Strength (SBS) from 51.3 MPa for the standard method to 70.2 MPa for the optimized method using the random blob impregnation technique (Figure 5b)) and the DVD chamber, which are largely above the average value given in the material datasheet



a) b)

Figure 4: a) Percentage contribution of the processing parameters on the void content in the repair patch with the wet impregnation method. b) Variation of Short Beam Strength of the repair patch as a function of measured patch void content.



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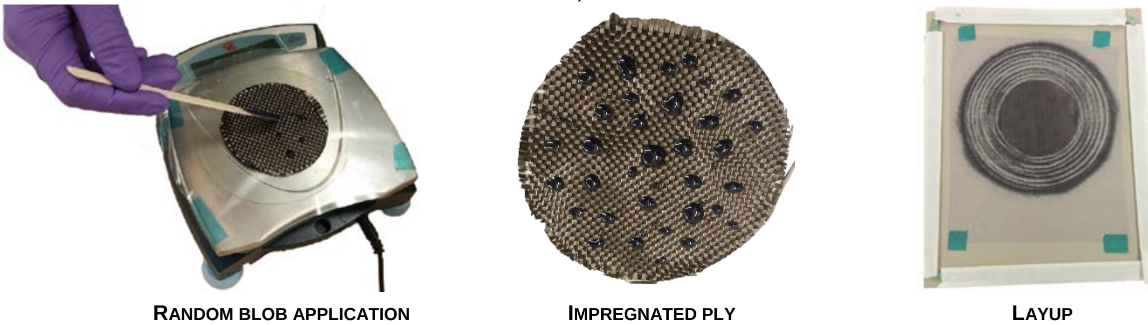
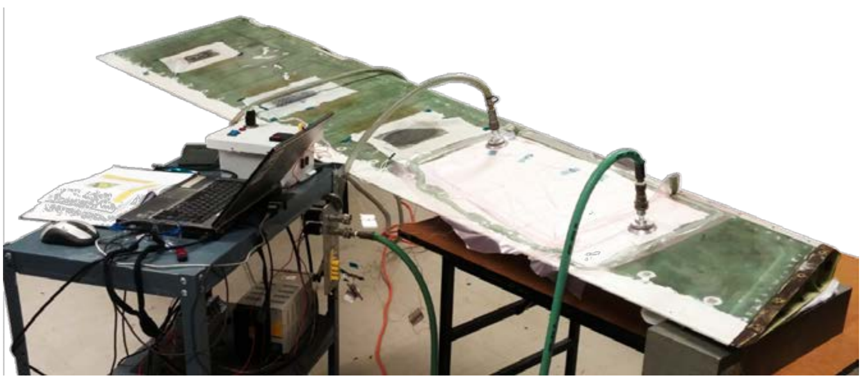


b)

Figure 5: a) DVD vacuum bag arrangement. b) Random blow impregnation method.

4 DEMONSTRATOR REPAIR IMPLEMENTATION

The laboratory scale prepreg and wet patch methods developed in this work were applied to a demonstrator repair part, an Airbus A320 elevator composed of thin-skinned sandwich panels (Figure 6). Repair processing steps were chosen to be as representative of a real repair scenario as possible. At eight locations, damage was simulated by a 75 x 100 mm rectangular cut-out through the external facesheet, around which each was scarfed with a GMI Leslie apparatus. The core was replaced in the simulated damage area for the prepreg repairs, but not for the wet layup repairs.



a)

Figure 6: Demonstrator repair setup.

Prepreg repairs were performed with two different carbon plain weave fabric prepregs: a semipreg and a conventional autoclave prepreg. The semipreg used Solvay/Cytec Cycom®5320 resin, impregnated at 36 wt % resin content into a 196 g/m^2 3k plain weave with T650-35 carbon fibres. The autoclave prepreg used was Cycom®977-2 fully-impregnated into a 196 g/m^2 3k carbon plain weave. The film adhesive used was FM®300-2M, with 293 g/m^2 weight, 0.25 mm nominal thickness and a non-woven polyester carrier. To splice the vertical sides of the core plug to the elevator's core, FM®410-1 foaming adhesive with 2.5 mm nominal thickness was employed. Since the same core material as originally used in the elevator was not available, a 96 kg/m^3, 3.175 mm cell size, 19 mm thick Nomex core was used instead for the core plug. This Nomex core provided similar stiffness and equivalent strength, but had to be manually sanded down to the 15 mm thickness required.

Only one two-part resin system, Henkel EA 9390 Aero, was used for the wet layup repairs. This resin served to both impregnate the repair plies and to bond the patch to the scarfed area. For the reinforcement, 200 g/m^2 dry carbon 3k plain weave fabric from Lincoln Fabrics was used. After scarfing, the elevator's remaining adhesive film generally fully closed off the cells of the exposed core. The occasional open cell was closed out with Magnolia Magnobond 77-4 A/B two-part epoxy syntactic potting compound. Processing parameters were varied for each patch to compare the improved methods developed here to baseline methods (Table 1). While each patch was cured with a heat blanket under a vacuum bag sealed to the external facesheet, processing data was collected on temperature gradients and pressure in the bag and core.

Carbon Prepreg	**Adhesive Perforation & Embossing**	**RT Debulk**	**Elevator Skin**	**Patch**
977-2	No Yes	20 min first/last ply	[+45/-45]	[-45/+45/-45/+45]
5320	No Yes	<10 min last ply		[-45/+45/-45/+45$_2$]

a)

Impregnation Technique	**DVD**	**RT Debulk**	**Elevator Skin**	**Patch**
Vacuum	No	1 h		
	Yes	No	[+45/-45]	[-45/+45/-45/+45]
Random Blob	No	1 h		
	Yes	No	[+45/0/0/-45]	[-45/+45/0/0/-45/+45]

b)

Table 1: Demonstrator test matrix. a) Prepreg patch repair. b) Wet patch repair.

As shown in Figure 7, repairs were inspected by several non-destructive testing (NDT) methods, to both spot any major defects and evaluate the detection capabilities by comparison with the destructive testing that followed. No major disbond or delamination was discovered in any of the repairs.

The embossed/perforated film adhesive yielded no improvement in porosity with the 977-2 prepreg (Figure 8a)), likely due to the 977-2's cure cycle which led to adhesive gelation at a much higher temperature of 144 °C. Such autoclave prepregs with 177 °C cure cycles in general do not seem suitable as a repair material. They yield very high patch and bondline void contents with such VBO processes, and the 177 °C cure risks surpassing the parent structure's glass transition temperature causing warping or damage. The embossed/perforated film adhesive yielded a void free bondline with the 5320 semipreg, but was slightly detrimental to the patch void content (Figure 8a). With the 5320 semipreg, a good quality repair was achieved even without embossed adhesive: for semipregs with high crimp fibre architectures such as plain weave, the embossed adhesive may not be necessary.

For the wet layup repairs, the DVD was the most important factor, significantly reducing porosity for both vacuum and random blob impregnation (Figure 8b). While resin impregnation method was less important, the random blob method led to slightly lower porosity than vacuum impregnation both with and without DVD.

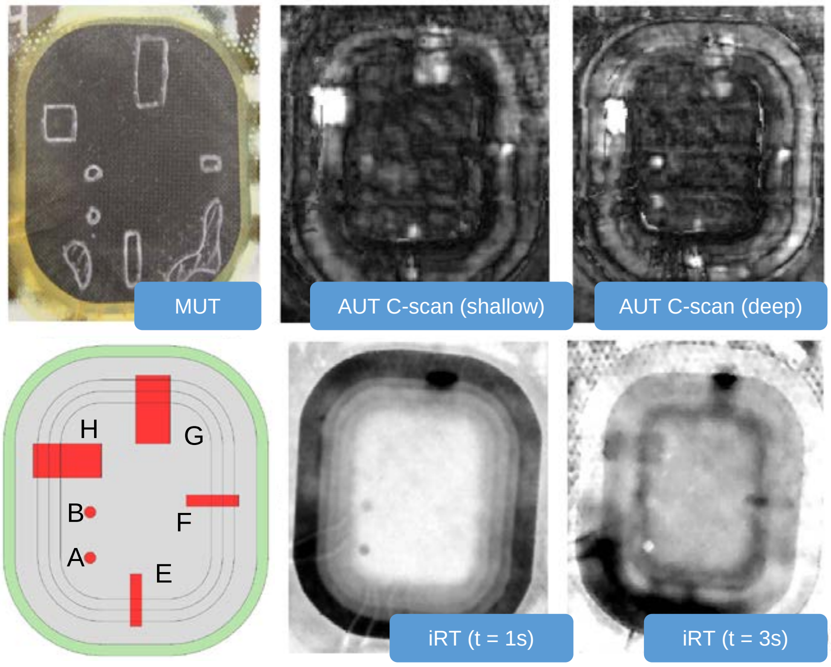
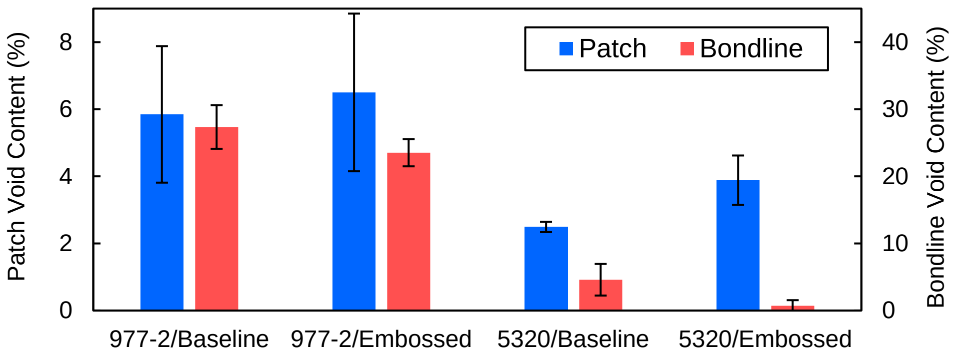


Figure 7: Prepreg (5320/baseline) reference standard NDT results. Artificial FEP film defects A-G were placed at different depths. NDT methods used were: manual ultrasound (MUT), automated ultrasound in a water immersion tank (AUT) and infrared thermography (iRT).



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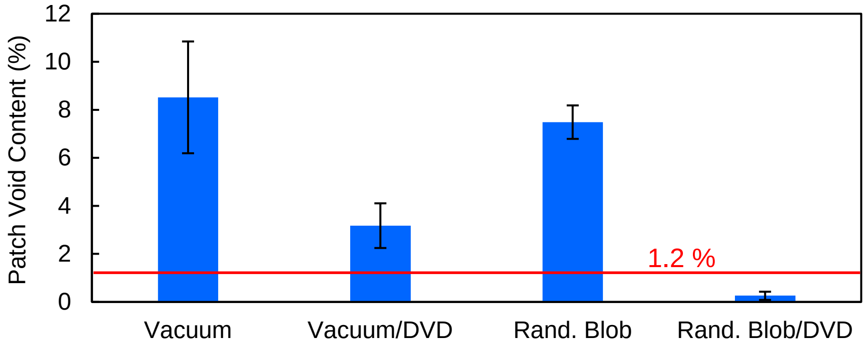

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Figure 8: a) Void content in the patch and bondline for the prepreg repairs. For patch void content, error bars represent the minimum and maximum values measured, while error bars represent the standard deviation for bondline void content. b) Void content in the patch for the wet layup repairs. The DOE study from the laboratory experiments predicted 1.2 % as the void content of the optimally processed patch.

Four point bending tests were performed on sections cut through each repair. However, these tests provided no useful information on strength recovery due to the elevator's stacking sequence not being suitable. Despite this, along with the NDT, these tests showed that the repairs had no major processing induced defects.

To assess the degree of cure, samples from each repair were tested by modulated differential scanning calorimetry (MDSC) and dynamic mechanical analysis (DMA). For the MDSC tests, the residual heat of reaction H_{res} was determined by integrating the non-reversing heat flow curve and normalizing for the resin mass. Degree of cure was then calculated from H_{res} using literature values for the total heat of reaction of each resin from [17-19], and is presented in Table 2. For each repair two measured values of glass transition temperature, T_g, are provided in Table 2 alongside literature values from [17, 18, 20]. The MDSC T_g was measured from the reversing heat flow curves, based on the half-height temperature definition of ASTM E1356 [21]. The DMA T_g was computed from the onset in storage modulus as per ASTM D7028 [22]. The results of Table 2 show that all prepreg repairs reached a high degree of cure. However, the DMA T_g results suggest the wet layup repairs may have been under cured. The repair patch stacking sequence may have lowered the DMA T_g values though, as 0° (span wise) laminates are known to lead to higher DMA T_g values than 45° laminates [23].

	977-2 Baseline	977-2/ Embossed	5320/ Baseline	5320/ Embossed	Vacuum	Vacuum /DVD	Rand. Blob	Rand. Blob/ DVD
MDSC (H_{res}) Degree of Cure (%)	98.3	99.9	100.0	99.1	99.4	99.0	99.0	99.3
MDSC T_g (°C)	180	(No data)	210	206	164	156	151	150
DMA T_g (°C)	179	182	197	193	105	117	120	135
Literature T_g (°C)	195	195	212	212	174	174	174	174

Table 2: Degree of cure and glass transition temperature (T_g) determined by modulated differential scanning calorimetry (MDSC) and dynamic mechanical analysis (DMA) tests on repair samples.

9 CONCLUSIONS

In this paper, robust processing protocols were developed using a science-based approach at the laboratory scale for prepreg and wet patch bonded repairs. An innovative bondline breathing strategy considerably reduced bondline porosity in a wide range of processing conditions. A robust wet patch impregnation method led to low porosity and improved mechanical properties in the repair patch. Both these techniques were applied to a repair demonstrator which identified scale-up challenges and confirmed the robustness and quality of the proposed methods.

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