Development of New Repair Technologies for Out-of-Autoclave Aircraft Composite Components

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ABSTRACT

The main objective of this work was to develop analytical tools and protocols for the design of composite bonded repair for primary aerospace structures manufactured with out-of-autoclave processing. 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. The optimized 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. 2D and 3D models were developed to analyze scarf and stepped repaired monolithic and sandwich composite joint under tensile loading. From an optimization perspective the search for an optimum shape of the repair patch was carried out. When a stiffener is present the adhesive shear stress state is affected depending on various geometric parameters such as: position to the repair, stiffener pitch, cut-out size, size vs pitch ratio. In order to validate the numerical results, a simpler and innovative experimental method of tests destined to replace a biaxial loading was developed.

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 main objective of this work was to develop analytical tools and protocols for the design of composite bonded repair for primary aerospace structures manufactured with out-of-autoclave processing. Specific objectives included:

1) Investigate the effects of processing parameters on the strength and durability of bonded repair.
2) Investigate the effects of the geometrical and material parameters on the strength and durability of bonded repair.

Figure 1 illustrates the approach used to develop robust processing protocols. 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.

2 MATERIALS

The materials used for repairs of monolithic composite laminates and sandwich panels using prepreg are: CYCOM 5320 T650 3K PW and CYCOM 5320 T650 3K 8HS prepregs, ECA –R 3/16 4 pcf and ECA-1/8 6 pcf honeycomb and FM 300-2M adhesive film. The materials used for repairs of monolithic composite laminates using wet lay-up are: 200 gm^2 dry carbon 3k (plain weave, four harness satin and 2 x 2 twill) fabric and two resins, Epocast 52 A/B from Huntsman and Loctite EA 9390 Aero from Henkel.

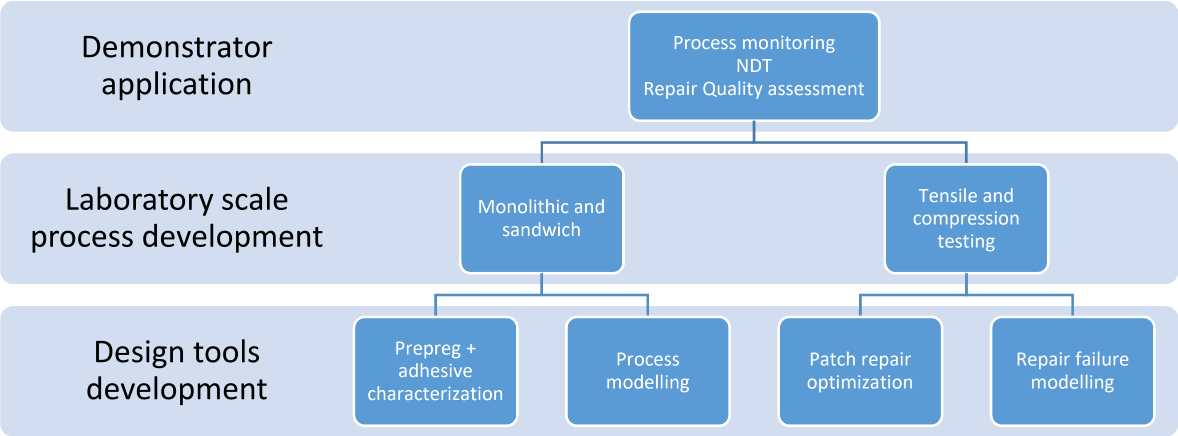


Figure 1-1: Task organization for the development of robust quality repair processes.

3 REPAIR PROCESSING DEVELOPMENT

While it is well admitted that voids have a negative impact in composite laminates, there is limited work and no clear agreement on the influence of bondline porosity on scarf repair properties recovery. Early work of Robson et al. [12] did not find correlation with the tensile strength of scarf repairs, because failure did not occur in the adhesive. Whittingham et al. [13] suggested that porosity should be lower than 2 % in the bondline; otherwise the adhesive load transfer capability is believed to be affected. Da Silva, et al. [14] found bondline porosity in single lap shear was only affecting final strength at higher temperature, when the adhesive was ductile. Recently, Salah [15] compared prepreg scarf repairs processed in and out-of-autoclave, and demonstrated strength reductions between 12–36 % for high porosity repairs in tension and compression, but no quantification of bondline or patch porosity was given. The quantification of the mechanical properties knockdowns caused by repair porosity is valuable information since repairs under vacuum bag only processing are likely to have high void contents.

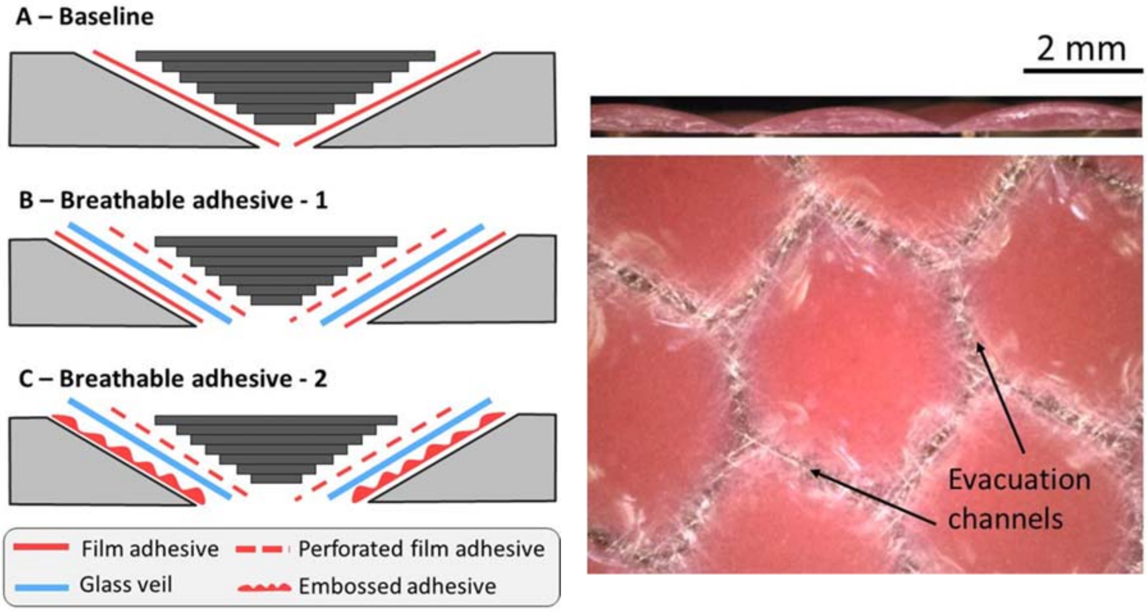
3.1 Breathable adhesive for prepreg patch repair

An adhesive film texturing process was developed to provide in-plane air evacuation capabilities, and produce high quality Vacuum Bag Only (VBO) bonded scarf repairs (Figure 3-1). This technological solution, also called embossing, consists of creating pathways for air to be extracted during the pre-cure room temperature vacuum hold. Using digital X-ray radiography, the solution was confirmed to eliminate entrapped air in the bondline. Internal patch porosity was also found to significantly decrease when a textured adhesive film was used, providing in-plane ply air evacuation. Thermal analysis showed that the embossing treatment had a limited effect on the thermal properties on the adhesive, but in-situ observations indicated that the air evacuation channels were sensitive to ambient temperature and compaction pressure, possibly limiting the effective air evacuation time. This texturing method is attractive because it is simple and can evacuate entrapped air out of large and thick scarf repairs of flat and curved parts using a single vacuum bag arrangement. Finally, since textured adhesive films are stable at low-temperatures and have similar handling properties as regular films, they could be readily available from materials suppliers for repair operations. Using the textured adhesive strategy, various scarf repair qualities were achieved and their residual strengths were measured. For different bondline thicknesses and scarf angles, the results indicated that the strength recovery of scarf repairs consistently increased in the order of 5–12 % for void-free repairs (Figure 3-2a). Furthermore, bondline porosity was found to induce changes in the failure mechanisms in bonded scarf repairs. Net-section failures in the composite adherent and patch were observed for void-free bondline; whereas a cohesive failure mode was noticed in the presence of porosity in the adhesive. These findings are useful for the design and qualification of repair processes.

Both analytical modelling and experimental observations indicated that moisture-induced porosity could be triggered by temperature deviations and loss of consolidation pressure, even for low moisture content in the repair materials. In this regard, recommendations to maximize repair pressure, limit pre-bond moisture and temperature variations were proposed. For the repair of honeycomb sandwich panels, low core pressure was found to be an important parameter to achieve good repair patch consolidation, which is consistent with the literature. Nonetheless, the influence of humidity in the honeycomb core, resulting of poor or partial pre-repair drying, led to various levels of core pressurization. As long as air evacuation was possible, core pressurization at elevated temperature was shown to have a relatively limited influence on the repair quality. This latter finding emphasizes that pre-cure gas evacuation is actually the key process parameter with partially impregnated prepregs to achieve high quality repairs. To this effect, a simple analytical model was used to generate a process window to determine the appropriate air evacuation time of repair patch of various sizes under different room temperature conditions. When air evacuation was successfully conducted, void-free adhesive was observed (Figure 3-2b). Non-Destructive Inspections could be performed, allowing the visualization of small potential disbonds, which is highly desirable for the long-term integrity monitoring and durability of a repair.

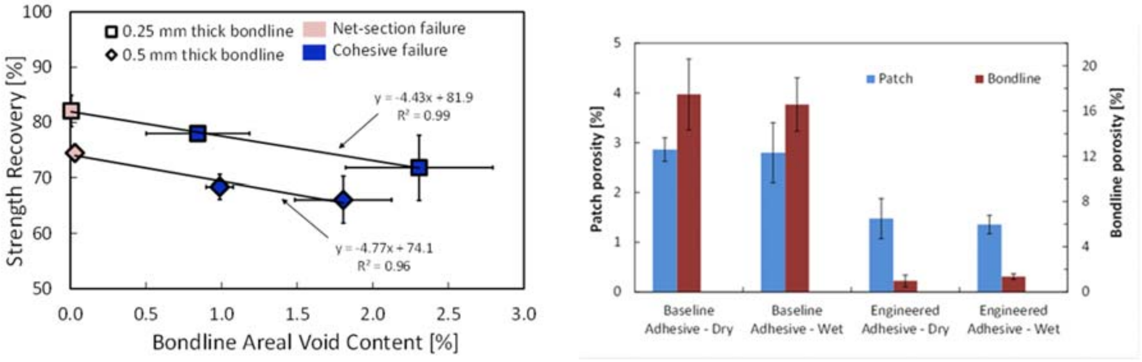
3.2 Novel wet layup impregnation procedure for patch repair

The effect of many different processing variables on void content was determined to design a robust, low void content process. At the lab scale, this optimal process was predicted and confirmed to yield 1.2±0.8 % void content, a significant improvement over current processes for which 7 % or higher is common. The key factors, in order of importance, were to: reduce the temperature at gelation to 93 ◦C, impregnate the dry fabric by either the vacuum or random blob techniques, perform a 2 h pre-cure vacuum hold and degas the patch by the Double Vacuum Debulk (DVD) technique (Figure 3-3). Factors with minimal effect on void content were vacuum level (as low as 50 kPa) and repair thickness.



a) b)

Figure 3-1: 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 3-2: 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.

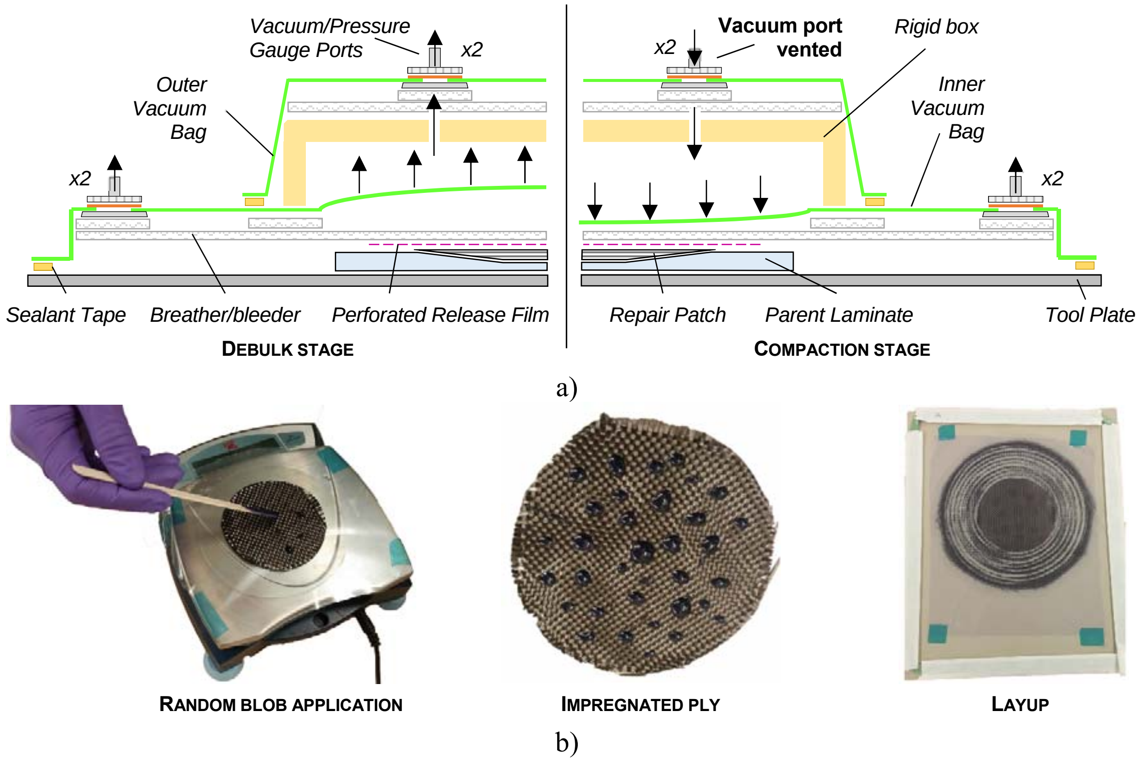


Figure 3-3: a) DVD vacuum bag arrangement. b) Random blow impregnation method.

4 REPAIR ANALYSIS TOOLS DEVELOPMENT

4.1 Joint geometry study for monolithic repaired laminates

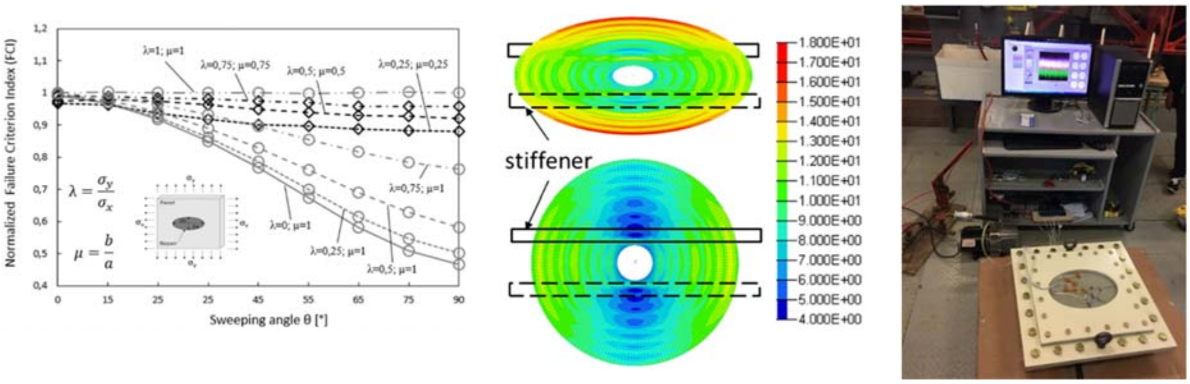
Using ABAQUS finite element software, a two-dimensional (2D) model was developed to analyze scarf-step repairs in monolithic composite laminates under tensile loading (Figure 4-1). The adhesive film was modelled between the parent and the patch and was considered as an isotropic elastic-plastic material. A shear failure criterion was used for the adhesive. The composite material was considered as linear elastic. A simple maximum strain fibre criterion was used to predict failure of the composite. The developed model was used to study the effects of: scarf angle, repair configuration (scarf/scarf versus scarf/stepped versus stepped/stepped repair), composite thickness, overply overlap length, overply orientation, use of a filler ply. Experimental work was conducted to validate the model predictions. Repair coupons were tested in tension at Room Temperature Dry (RTD), Elevated Temperature Dry (ETD) and (Cold Temperature Dry (CTD). Two scarf angles (3° and 7°) were tested at RTD and ETD conditions. Pseudo “Hot/wet” tensile tests were performed to investigate the effect of the overply on the repair strength. Based on the work of Collings et al (1983), a hot/wet testing environment was simulated by using a more elevated temperature. From data obtained in the literature, a test temperature of 121 °C was determined to simulate a test at 82 °C on a specimen having 2.6% moisture content in the adhesive film. Tensile tests results showed that the specimens with the overply had a higher strength and that failure occurred in the patch and along the adhesive bondline. Repaired specimens were tested in fatigue at RTD. A residual strength test was performed on a specimen that was tested at 30% static strength for one million cycles. Results showed that the residual strength was the same as the static strength. The effect of the overply on the fatigue life was investigated. Fatigue tests were performed with a stress level of about 50% of what was measured in the static test. The specimens with an overply had a fatigue life 3.6 times longer than specimens with no overply.

Figure 4-1 Model geometry.

4.2 Optimization of the repair shape

New literature studies and late 2014 FAA new regulation pointed out the importance of repair cutout as well as the remaining strength needed after a failed repair. A procedure of optimization of the patch repair shape was conducted with parametric analytical models (Figure 4-2a,b). The 2D and the 3D finite element studies emphasized the non-uniform stress distribution within the bond surface. From an optimization perspective, the search for an optimum repair patch shape was performed. It was also shown that under uniaxial and biaxial loading a non-circular patch can reduce the stress concentrations with up to 40% less material removal.

In order to validate the numerical results, a simple and innovative test fixture was developed to replace a biaxial testing rig (Figure 4-2c). An instrumented rig was designed where out-of-plane loading was applied by hydrostatic pressure on of the repaired panel with various clamping boundary conditions. Circular and elliptical repairs were performed on monolithic quasi-isotropic composite plates. The repairs were instrumented in order to confirm the uniformity of the stresses. The testing rig also measures the ultimate load of the repair patch and analyses the failure modes. It was found that the stress distribution in the bonded region should be as uniform as possible in order to avoid the peaks that can initiate failure. Furthermore, the rig design enable the investigation of the patch repair performance under cycling loading.



a) b) c)

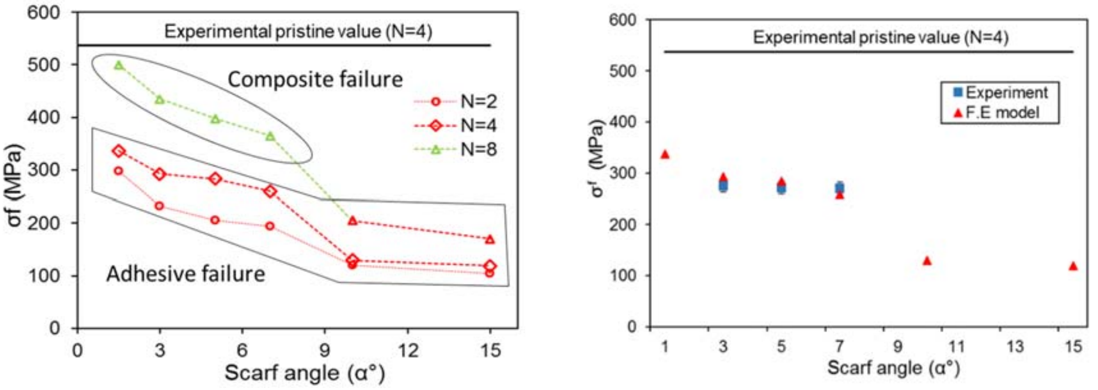
Figure 4-2 a) Optimum repair under biaxial loading, b) Stiffener effect on adhesively scarf repair, c) Biaxial loading testing rig.

4.3 Joint geometry study for repaired sandwich panels

PW and 8HS sandwich panels were manufactured and tested. Only the tool face skin was repaired. The repair was across the whole specimen width. The baseline value for the scarf angle was 3o. The overall specimen dimensions varied as a function of the test conducted on the specimen. Compressive, tensile and flexure tests were conducted on both pristine and repaired panels. For the flexure tests, the repair was tested both in tension and in compression. Tensile tests were also performed on the repaired skin that was extracted from the panel. The results of the flexure tests correlated well in terms of strength with the tensile and compressive tests results. However, the tests conducted on the repaired skin showed that the strength was lower than the one of the repaired sandwich panel. A finite element analysis confirmed that stresses in the bondline were higher for the extracted repaired skin than for the repaired sandwich panel.

Using ABAQUS finite element software, a two-dimensional (2D) model was developed to analyze scarf-step repairs in sandwich composite panel under tensile loading. The adhesive film was modelled between the parent and the patch and was considered as an isotropic elastic-plastic material. A shear failure criterion was used for the adhesive. The composite material was considered as linear elastic. A simple maximum strain fibre criterion was used to predict failure of the composite. The geometrical design parameters investigated are the scarf angle (α), the number of plies (N) and the overlap length of the overply (Lo). The influence of these parameters on the shear and peel stress distributions along the bondline of the stepped-scarf joint was investigated. The strength of the repaired sandwich panel was also predicted and compared with the one of the pristine panel (Figure 4-3a).

The model predictions were validated by experimental work (Figure 4-3b). Repairs were performed using the baseline configuration but with three different scarf angles (3°, 5° and 7°) and tested in tension at RTD. Moreover, sandwich specimens were repaired using the baseline configuration but with the addition of a (+45/-45) over-ply with an overlap length equal to 10 mm and tested in tension at RTD. Correlation between experimental and finite element results was very good.

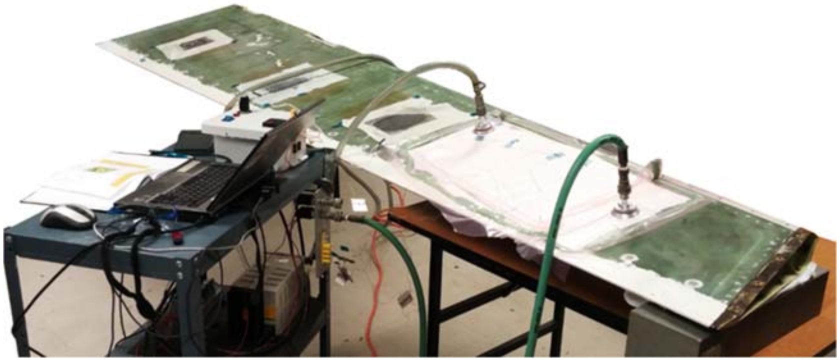


a) b)

Figure 4-3: a) Effect of scarf angle and number of plies on patch repair strength of repaired sandwich panels. b) Validation of repaired sandwich panel modelling.

5 REPAIR DEMONSTRATOR

At the lab scale, the impregnation technique was the second most important factor to both void content and fibre volume fraction. Only the two optimal methods, the vacuum and random blob impregnation techniques, were applied to the demonstrator (Figure 5-1). For the demonstrator this factor proved less important than the DVD process, with the random blob method leading to a slight improvement in void content compared to the vacuum impregnation technique. The DVD factor had only a 10 % contribution to void content. However, this was likely a result of poor temperature control: in a follow-up test with the temperature control problem corrected, patch void contents below the predicted optimum (0.68 %) and approaching autoclave quality were achieved. Consequently for the demonstrator the DVD technique proved more important: patch void contents of less than 3 % were achieved when DVD was used compared to 7.5 % or higher without. The embossed and perforated film adhesive led to a void free bondline when used with semipreg, although provided no improvement in the patch void content. Without this engineered adhesive, a low porosity repair was still achieved with the semipreg, perhaps indicating it is not needed with high crimp (plain weave) semipregs. No improvement in bondline or patch void content was achieved when the engineered adhesive was used in conjunction with the autoclave prepreg. Further experiments would be needed to explain why. Semipregs showed good promise as a repair material, yielding much lower patch and bondline void content than the autoclave prepreg. The lower cure temperature of the semipregs relative to autoclave prepregs can also be beneficial to avoid warping or damaging the parent structure. The demonstrator implementation also served to highlight typical process deviations experienced in the field: in-plane and through-thickness temperature gradients, hotter and more humid ambient conditions than most controlled laboratory environments and a large variation in vacuum quality due to both available equipment and leaks.



a)

Figure 5-1: Demonstrator repair setup.

6 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 new 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 who identified scale-up challenges and confirmed the robustness and quality of the proposed methods. Repair mechanical modelling tool were developed and were able to predict repair strength and failure mode. Parametric study identified the fundamental knowledge of repair behaviour and enabled the repair shape optimization to minimize repair stresses. When implemented on the demonstrator, overall the optimized wet layup methods developed in this work and the improved semipreg methods with air breathable adhesive led to significant quality and robustness improvements relative to baseline methods. Implementing these new procedures in practice could provide improved mechanical property recovery, durability and inspectability. This may help address certification challenges with co-bonded repairs and expand their scope to structural repairs currently reserved for less efficient bolted repairs.

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