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# Processing of co-bonded scarf repairs: Void reduction strategies and influence on strength recovery

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ABSTRACT

Partially impregnated prepreg are attractive materials for scarf bonded repairs as they can be consolidated with vacuum assisted pressure only. Several air evacuation strategies were evaluated for cobonded scarf repairs of monolithic composites skins. Various void levels were measured in the bondline by digital radiography, and tensile tests were performed to assess the repairs strength recovery. Most of the entrapped air could be evacuated prior to cure for the method using a textured adhesive film. This repair strategy consistently led to a significant reduction in bondline porosity and exhibited the highest strength recovery. Overall, it was found an average linear reduction in tensile strength recovery of 4.5% per 1% areal void content in the adhesive. Additionally, a change in final failure mode was observed from cohesive failure for porous bondlines, to net-section tensile failure in case of void-free bondlines.


## 1. Introduction

### 1.1. Background

While in use, from ground service vehicle bumps to in-flight hail or lightning strikes, airframes experience damage. With the growing use of composite materials for primary and secondary aerospace structures, the demand for cost-effective, reliable, and durable repair procedures of composite structures is gaining momentum in industry [1]. Currently, aircrafts' Structural Repair Manuals rely on structural bolted repairs as bonded repairs are limited to repair sizes that ensure limit load residual strength capability with the patch departed [2]. However, bonded scarf repairs present numerous advantages over bolted repairs such as higher strength and stiffness recovery, low-weight, and aerodynamic smoothness [3]. The remaining challenges associated with bonded repairs are on post-repair inspection, airworthiness certification, process automation, as well as a better understanding of materials, process and quality relationships [1].

### 1.2. Design and processing of bonded scarf repairs

In adhesive joints and repairs, the adhesive mainly experience shear and peel stresses. Near-flush-surface scarf repairs provides the highest joint efficiency compared to overlap or doubler bonded repairs, by reducing peel stress at the ends of the bondline [4]. A key design parameter is the scarf angle; a small scarf angle improves the general strength of the repair by decreasing the average and peaks shear stresses and in the bondline, as well as reducing the peak peel stress. Over-laminate plies are also proven to reduce peel and shear stresses by locally increasing the bond stiffness. Bondline thickness is another critical design parameter, ply thickness to adhesive thickness ratio above 1.5 was shown to significantly increase peaks in shear and peel stresses, reducing the overall scarf repair strength [5].

Similarly to composite component, the quality and the resultant performance of bonded repairs are dependent on their processing. After inspection of the damage area, repairs of components involve a series of steps: removal of the damaged plies, scarf of the parent structure, surface preparation, adhesive application and patch consolidation, post-repair inspection, and refinishing. If the repair process is inadequate, poor patch consolidation can lead to patch wrinkles, bondline thickness variation, voids, and debonds [6]. To mitigate defect formation, several processing aspects have been studied for the repair of monolithic laminates. This includes the prediction and control of temperature gradients during cure caused by the localized heat application by means of heat blankets [7]. The effect of pre-bond moisture on repair quality [8,9], mechanical strength [8,10], including fracture toughness [11,12] has been widely studied. Patch consolidation and void mitigation are the focus of this study.

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### 1.3. Porosity sources and mitigation strategies under vacuum bag only pressure

When repairs are performed directly on large components, relying on an autoclave or mechanical systems to add further consolidation pressure to the repair area and collapse voids is usually not possible. Therefore, under atmospheric pressure only, any entrapped air is likely to generate unacceptable levels of porosity.

A common practice to improve quality of vacuum pressure processing of bonded repairs is the use of a technique called Double-Vacuum Bag Debulk (DVD) [13,14]. This approach consists of the addition of a second vacuum bag around a conventional bag by means of a rigid box. The DVD setup initially enables the prepregs to be degassed at full vacuum without external consolidation pressure applied to the repair patch. Then, after the second bag is removed, full vacuum pressure is applied to consolidate the prepreg stack. Despite reduction in void content achieved with the DVD technology over a single vacuum bag for high-volatile content prepreg systems (up to 14%), this low-cost out-of-autoclave method remains heavy and time-consuming to implement [14].

Another strategy to reduce porosity in bonded repairs under vacuum bag consolidation pressure only is the use of recently developed Out-of-Autoclave (OOA) prepregs [15]. These high fibre content and quasi-zero bleed materials systems are desired for structural repairs, as can be processed at relatively low temperature (93–121 °C) under ambient pressure only (1 atm) [16]. These partially impregnated prepregs feature dry fibre regions which act as evacuation channels, allowing entrapped air and volatiles to escape during an ambient temperature vacuum hold. Then, during the heat ramp, dry regions are impregnated with the resin, yielding after cure quasi void-free laminates out of the autoclave [17].

To achieve good consolidation, the recommended air evacuation strategy in OOA prepregs is in-plane, and relies on edge breathing. However, in a scarf repair scenario, patch prepreg plies are fully surrounded by pristine parent materials, and the only air evacuation capability is through-the-thickness. Various researchers performed gas flow measurements to characterize the in-plane and transverse air permeability of semi-impregnated prepregs [18–20]. An agreement emerged on the highly anisotropic nature of air permeability in partially impregnated prepreg. The results showed that the transverse air permeability was at least three orders of magnitude lower than in-plane permeability, at $10^{-17}$ m$^2$ vs $10^{-14}$ m$^2$, respectively. Kratz and Hubert [18] showed that low crimp level and 'tight' fabric architectures exhibited even lower value of transverse air permeability, reducing further the capability to extract entrapped air. It is also worth to note that whereas the in-plane permeability was not affected by laminate thickness, the through thickness air permeability decreased with increased stack thickness, with some material systems exhibiting no transverse air flow for up to 24 h.

Therefore, in a scarf repair cavity, only transverse air evacuation is possible, however it is low, or negligible. To mitigate air entrapment and subsequent unacceptable levels of porosity in co-bonded repairs with partially impregnated prepregs, Preau et al. [21] used a dry glass fabric within the adhesive film, providing evacuation channels at the ends of the semi-impregnated repair plies. Through microscopic analysis, a significant reduction in patch and bondline void content was achieved when a dry media was placed within the adhesive. In a work on bonded repairs for carbon/bismaleimide composites, Rider et al. [22] used a permeable fabric layer at the adhesive composite interface to provide a pathway within a staged adhesive film. With this strategy, entrapped-air-induced voids were reduced, and staging of the adhesive film Cytec FM® 32 decreased volatile induced porosity in the bondline. Finally, another approach could be to use a partially impregnated material that allows transverse breathability. Recently, Grunenfelder et al. [23] studied an in-house-developed partially impregnated prepreg system with increased transverse permeability. Rather than relying on a conventional uniform continuous resin film coating the fibre bed, this "two-side tacky" prepreg material featured a discontinuous resin distribution that allowed through thickness pathways for air evacuation. The introduction of transverse breathability was shown to reduce surface and internal porosity.

### 1.4. Porosity influence on mechanical properties

Various authors have largely reported that voids induce significant reductions in matrix dominated properties, such as the interlaminar shear and flexural strength of laminates [24–27]. Voids are found to promote crack initiation and/or propagation [24], and it is commonly stated that there is an average 4–6% reduction in interlaminar shear strength per volumetric unit of void content in composite laminates.

While it is well admitted that voids in composite laminate have a negative impact on the mechanical performance, there is limited work and no clear agreement on the influence of bondline porosity on scarf repair properties recovery. Parker [9] showed that pre-bond moisture influenced adhesive porosity. Using early materials systems, his results indicated that joint strength was reduced with higher bondline void content and pre-bond moisture, and that increasing levels of adhesive porosity caused changes in joint failure mechanism from cohesive or adherent to interfacialfailure for some adhesive systems. Later, Robson et al. [8] did not find correlation with the tensile strength of scarf repairs, because failure did not occur in the adhesive. Whittingham et al. [6] recently suggested that porosity should be lower than 2% in the bondline; otherwise the adhesive load transfer capability is believed to be affected. The quantification of the knockdowns in mechanical properties caused by repair porosity is valuable information since repairs under vacuum bag only processing are likely to have high void contents.

## 2. Objective and approach

In this paper, various processing strategies were implemented to overcome the lack of transverse air evacuation in semi-impregnated prepregs to process bonded scarf repairs under vacuum consolidation pressure. Repair quality and porosity were assessed by optical microscopy and digital radiography prior to mechanical testing. Post-mortem analysis of fractured specimens, linked with mechanical tests results and repair quality were used to quantify to what extentbondline porosity affects the static repair strength recovery and how the failure mechanisms of co-bonded scarf repairs processed under vacuum pressure may be influenced by internal quality.

## 3. Experimental methodology

### 3.1. Materials

The semi-impregnated material selected for the parent laminates and repair patches was Cytec Cycom® 5320 epoxy resin with a plain-weave (PW) carbon fibre architecture (T650-35 3K), with an areal weight of 196 g/m$^2$, and a resin content of 36% by weight. To achieve the desired bondline thickness, which varied in this study, two versions of the popular adhesive film Cytec FM® 300-2 were used for co-bonding the repair plies into the scarf repair cavity. FM® 300-2U is a thinner and unsupported version of FM® 300-2M.