

# TOWARDS OPTIMIZATION OF COMPOSITE REPAIR PATCH MANUFACTURING FOR AUTOMATED FIBER PLACEMENT

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## ABSTRACT

Repair involving composite patches are widely used in the aerospace industry as they allow for extended service life for aging aircraft structures and reduced turnaround time for aircraft to get back in the air. However, repairs in the field are currently performed manually; extensive training is required to acquire the skills needed for surface preparation and adequate repair patch application. The focus of this study is to investigate the manufacturability of adhesively bonded composite scarf repair patches using automated fibre placement (AFP). A simulation of the automated process for repair patch manufacturing was performed and a finite element model was built to examine stresses in the repair patch and the adhesive layer when subject to in-plane tensile loading. Two distinct repair patch shapes were investigated. The first model consisted of a circular repair patch replicating typical manual scarf repair with circular layers. The second model represented an AFP produced repair patch consisting of several layers of discrete composite tows with straight-edge endings. The resulting mechanical behavior for both repair patch shapes was assessed and compared by analyzing stress peaks and stress distribution in the composite repair patch layers and in the adhesive layer. The results and analysis presented may provide a guide to repair and research engineers wishing to use AFP technology for composite repair patch manufacturing.

## 1. INTRODUCTION

The use of advanced composites in the aerospace industry has been steadily increasing over the past few decades due to their excellent specific strength and stiffness and high fatigue life. However, composites are prone to damage caused by low-energy impacts like bird strikes and tool drops. As a consequence, efficient and cost-effective repair methods for composite structures are of increasing interest [1-3].

Common repair techniques for composite parts include applying a repair patch to restore structural efficiency and strength with the patch being either mechanically fastened or adhesively bonded. Adhesively bonded repairs have been shown to be cost-effective and provide uniform load transfer across the damaged area [4-5]. Bonded repairs can either be single sided (unsymmetrical) or double sided (symmetrical) and can take the form of a scarf repair patch or be externally bonded. Scarf repairs are typically used to restore load-carrying capacity and meet flushness requirements. In scarf repairs, the damaged material is removed and the repair area is scarfed with the desired taper ratio creating a cavity in which the repair patch can be placed.

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The available literature on composite repair patches applied to metallic parts is extensive [6-10]. However, as aircraft manufacturers move towards increased use of composites in their new generation aircraft (e.g. Boeing 787 and Airbus A350X [11]) more research focus needs to be placed on the application of repair patches to damaged composite parts. Current regulations assume that the repair patch does not restore any load-carrying capacity when certifying repairs applied to primary (or flight-critical) structures due to the risk of patch debonding and delamination [12]. The likelihood of such patch failure can be reduced through appropriate design and manufacturing. However, repairs in the field are currently performed manually and the quality and surface finish of the repair relies solely on the available tools and the skills of the operator. Furthermore, extensive training is required to acquire the skills needed for surface preparation and adequate repair patch application when considering composite on composite repair. Automated processes using CNC machinery are increasingly being used in aerospace manufacturing to increase efficiency, repeatability and accuracy. However, further work considering automated manufacturing methods for composite repair patch fabrication is required.

It is thus the focus of this study to investigate the manufacturability of single-sided composite scarf repair patches using automated fibre placement (AFP). A simulation of the automated process for repair patch manufacturing was performed and a Finite Element (FE) model was built to examine stresses in the repair patch and the adhesive layer when subject to in-plane tensile loading. FE modelling was performed for two distinct repair patch shapes. The first model consisted of a circular repair patch replicating typical manual scarf repair with circular layers. The second model represented an AFP produced repair patch consisting of several layers of discrete composite tows with straight-edge endings. The FE models considered a scarf repair applied to a parent structure consisting of 32 layers of AS4 3501-6 carbon/epoxy composite laminate with a taper ratio of 50:1. The repair patches consisted of an eight-layered layup matching the parent structure ply-by-ply. The parent structure was considered to be under an in-plane tensile load of 160 kN ( $\sigma = 50$  MPa). The resulting mechanical behavior for both repair patch shapes was then assessed and compared by analyzing stress peaks and stress distribution in the repair patch and the adhesive layer.

## **2. COMPOSITE REPAIR PATCH MANUFACTURING USING AFP**

### **2.1 Automated Fibre Placement**

Automated Fibre Placement consists of placing composite prepreg strips, called tows, which have unidirectional fibers pre-impregnated with resin. The composite tow bands are collimated on the AFP composite head mounted on an industrial robot and placed on a tool or mold [13-16]. The prepreg tape is either stored on the composite head or delivered to the head from a creel cabinet. The material is then delivered to a compaction roller where additional heat and force are applied to the material before placement as shown in figure 1 (adapted from [17]). The implementation of such automated technologies is heavily influenced by the AFP equipment capabilities with key parameters including minimum cut length, turning radius, tow-drop areas and the use of either non-rotatable or rotatable cutters [18]. The robot program that controls process speed and position is developed off-line using software packages. Automated manufacturing methods such as high-speed fibre placement enhance productivity by increasing composite layup rates. Indeed, aerospace companies have claimed reductions in man hours of up to 70 – 85 %, and scrap rates reduced to 5 % instead of 25-30 % with manual layup [5].

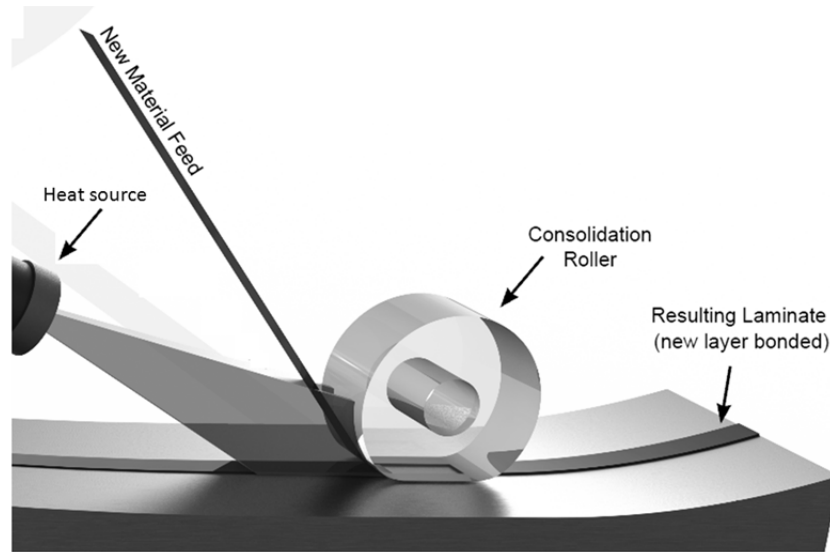


Figure 1: Automated Fibre Placement process

## 2.2 Geometry and AFP Properties

A simulation of the automated process for repair patch manufacturing was performed using Vericut Composites Programming (VCP). The repair patch consisted of eight layers of AS4 3501-6 carbon/epoxy composite laminate with layup  $[-45/0/45/90]_s$ . Each layer of carbon/epoxy was 0.2 mm thick while composite tow width was 6 mm. The repair patch was tapered with a 50:1 taper ratio. The design of the repair patch layers consisted of circular boundaries which increased in diameter from 40 mm at the bottom of the taper to 200 mm for the top layer of the repair patch. The cutting mechanism used for cutting the composite tow was considered to be non-rotatable resulting in straight tape endings.

The top layer of the circular repair patch layup generated in VCP is shown in figure 2 (a). The results highlight the tow-boundary overlap as a key parameter as it dictates the tow length. Indeed, for the circular patch the tow is set to end when the ply area is fully covered by the prepreg tape which results in the tape over-extending past the ply boundary as shown in figure 2 (b). This can result in thickness build-up and overlaps which when compounded over several layers can create mismatch between the parent material and repair patch plies as well as generate stress concentration areas. If the tow is set to end when the centerline hits the ply boundary, as shown in figure 2 (c), gaps appear between the composite tape and the ply boundary which can result in both overlaps and resin-rich areas. In this study the repair patch layers were designed with no overlap of the composite tow over the ply boundary and the resulting gaps were considered to be filled with the adhesive FM300 as seen in figure 3(a). This eliminates potential material build-up or overlaps as shown in figure 3 (b).

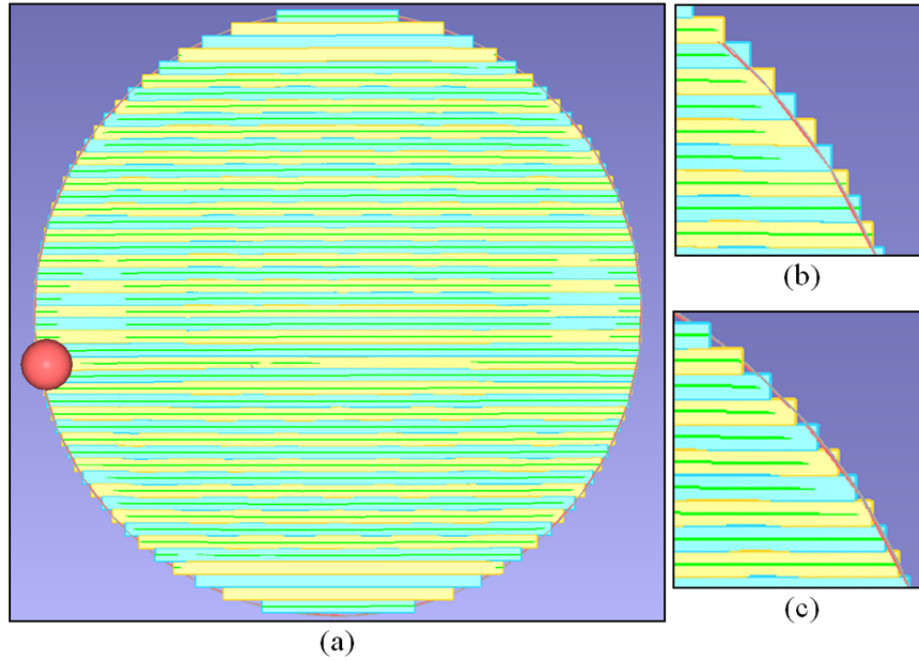


Figure 2: (a) Circular patch layup, (b) adjusted tow/boundary overall (full coverage), (c) partial tow/boundary overlap (tow meets ply boundary)

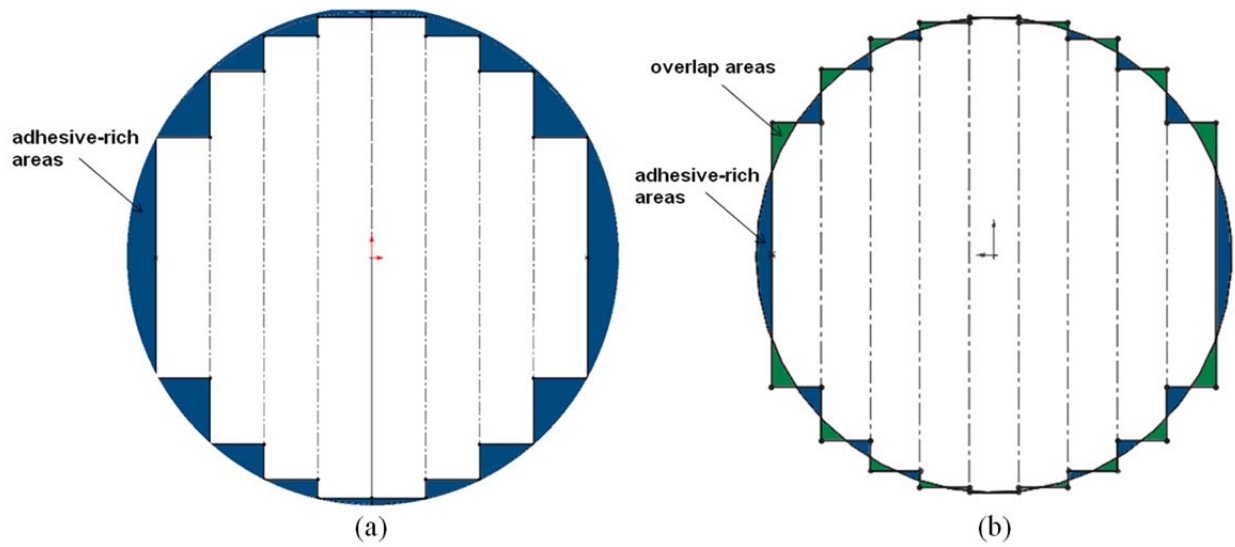


Figure 3: (a) AFP repair patch outline with no overlap and (b) with partial tow-boundary coverage

### 3. FINITE ELEMENT MODEL OF THE REPAIRED PANEL

#### 3.1 Geometry and Material Properties

FE modelling and analysis of an adhesively bonded repair patch applied to a scarfed composite part was carried out using ANSYS 14.5. The parent structure consisted of 32 layers of AS4 3501-6 carbon/epoxy composite laminate with layup  $[-45/0/45/90]_{S4}$ . Each layer of carbon/epoxy was 0.2 mm thick. The length, width and thickness of the parent structure were 500 mm, 500 mm and 6.4 mm respectively. The damaged material is assumed to have been removed and the repair area scarfed with a taper ratio of 50:1. The part was repaired with a composite patch consisting of an eight-layered AS4 3501-6 carbon/epoxy composite laminate with layup  $[-45/0/45/90]_S$  matching the parent structure ply-by-ply as shown in figure 4. FM 300 adhesive with a thickness of 0.2 mm is used to bond the repair patch to the parent structure. The panel was considered to be under in-plane tensile load of 160 kN ( $\sigma = 50$  MPa) as shown in figure 5. Linear static analysis only was performed. The material properties of AS4 3501-6 carbon/epoxy material and the adhesive are shown in table 1. The model featured three main sections: the parent structure, the adhesive layer, and the repair patch. Each composite ply and the adhesive layer had one element through the thickness using layered shell elements. Face meshing was applied across each composite ply and the adhesive layer to enhance the aspect ratio and uniformity of the mesh. Also, mesh refinement across the repaired area was performed to optimize FE results. Top view of the models built for the circular patch and the AFP produced patch is shown in figure 6.

Table 1: Material Properties for AS4 3501-6 and FM 300 [19]

Property	AS4 3501-6	FM 300
$E_1$ (GPa)	128	1.02
$E_2 = E_3$ (GPa)	13	
$G_{12} = G_{23} = G_{31}$ (GPa)	7.2	0.39
$\nu_{12}$	0.30	0.30

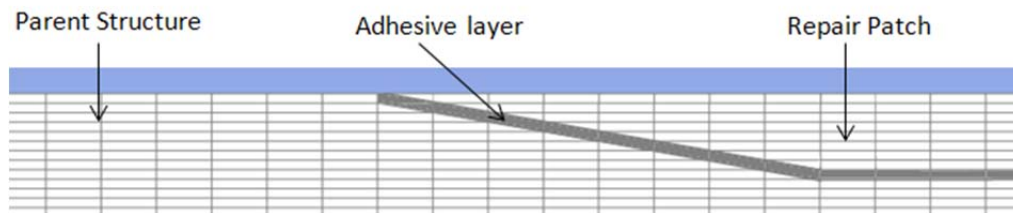


Figure 4: Adhesively bonded scarf repair patch applied to a composite panel

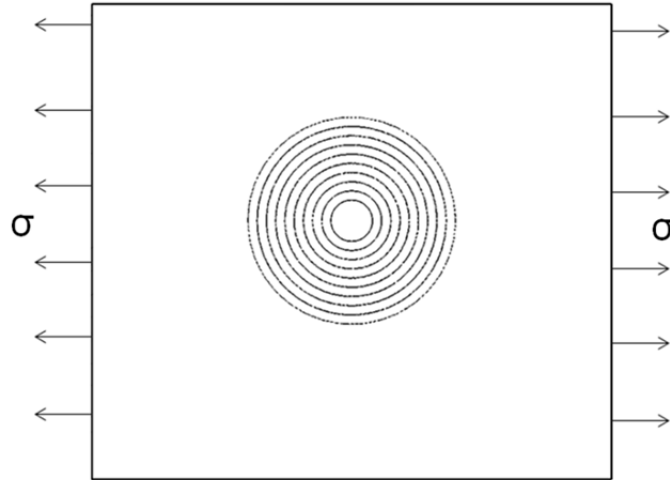


Figure 5: Panel and patch boundary and loading conditions

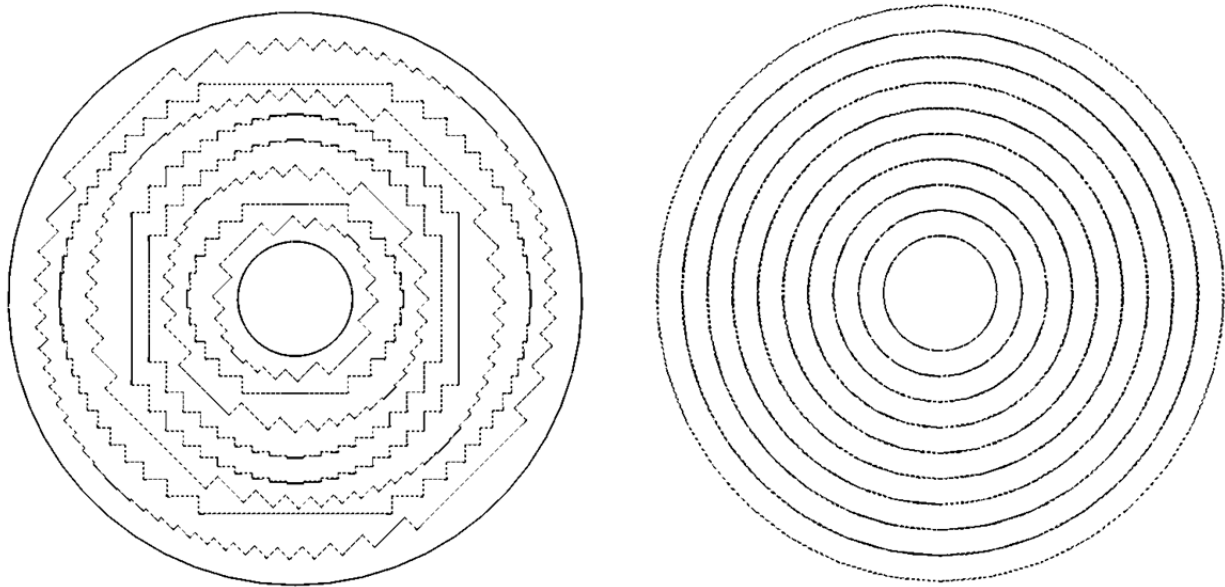


Figure 6: AFP repair patch (left) and circular repair patch (right)

### 3.2 Results and Discussion

This study analyses the mechanical behavior of both repair patch shapes by comparing stress peaks and stress distribution in the repair patch and the adhesive layer. As such, stresses in the principal material directions ( $\sigma_{11}$ ,  $\sigma_{22}$ ) and in-plane shear stress ( $\sigma_{12}$ ) for each ply of the repair patch and in the adhesive were investigated. Indeed, the orthotropic nature of fibre-reinforced

composites means that strength is a function of orientation relative to the principal material directions and as such this study focuses on stresses experienced at the lamina level. Lamina failure is typically due to resin fracture, resin cracking or fibre fracture when subject to longitudinal tension and high stress/strain concentrations around the fibre which leads to interface failure when under transverse tension. Excessive in-plane shear stress can result in failure due to stress concentration appearing at the fibre-matrix interface. Also, the adhesive/composite interface is critical as patch failure can be caused by debonding of the patch due to excessive shear stress in the adhesive layer.

### 3.2.1 Composite Repair Patch

Figures 7, 8 and 9 show stresses  $\sigma_{11}$ ,  $\sigma_{22}$  and  $\sigma_{12}$ , respectively, for both traditional circular repair patch and AFP produced patch for each ply. Longitudinal stress values  $\sigma_{11}$  show high stress levels at layers with  $0^\circ$  fibre angle as they are in line with the loading direction and hence carry most of the load. Transverse stress values  $\sigma_{22}$  show high stress levels at layers with fibre angles at  $90^\circ$  and shear stress values  $\sigma_{12}$  show peak stress levels at  $\pm 45^\circ$  layers. The results are in line with elementary mechanics of composites principles. It can be observed that stresses  $\sigma_{11}$ ,  $\sigma_{22}$  and  $\sigma_{12}$  for the AFP produced patch are higher by up to 5 % compared to the circular repair patch. This is due to the considerable changes required in the repair patch shape to accommodate for the AFP method which resulted in a smaller surface area for the patch layers causing a higher load being carried by the AFP repair patch plies.

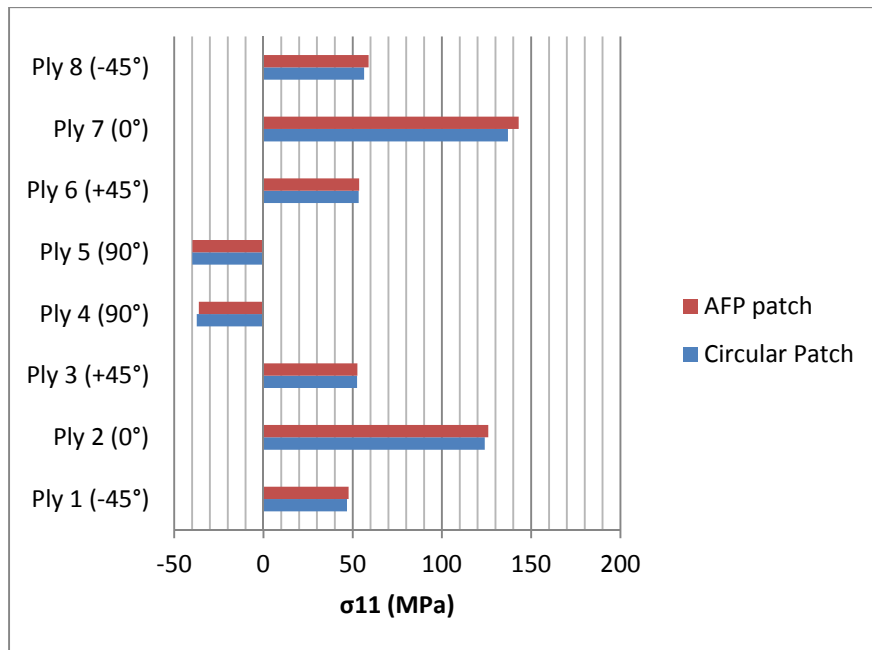


Figure 7: Stress  $\sigma_{11}$  for traditional circular patch and AFP circular patch

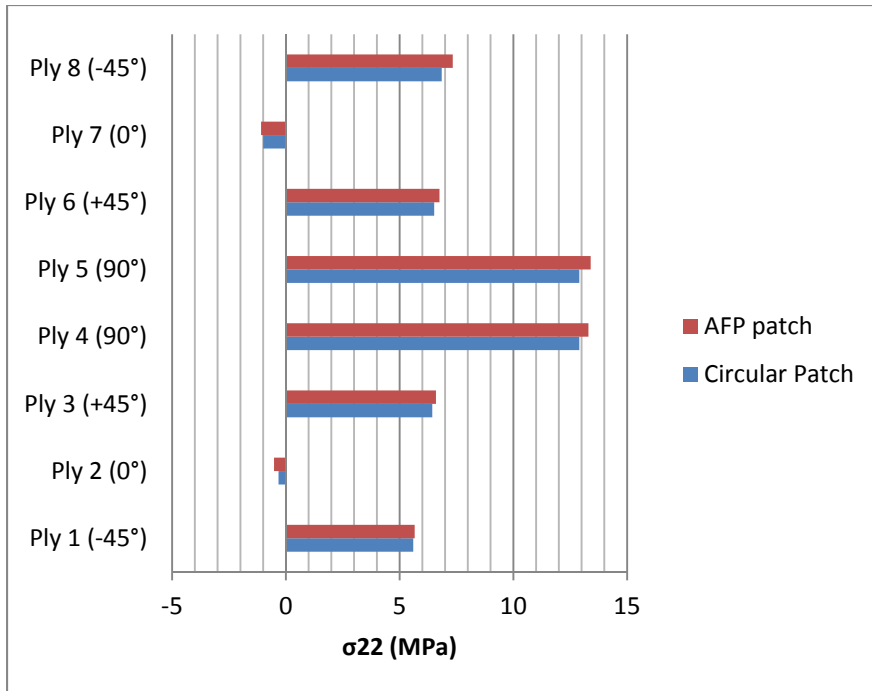


Figure 8: Stress  $\sigma_{22}$  for traditional circular patch and AFP circular patch

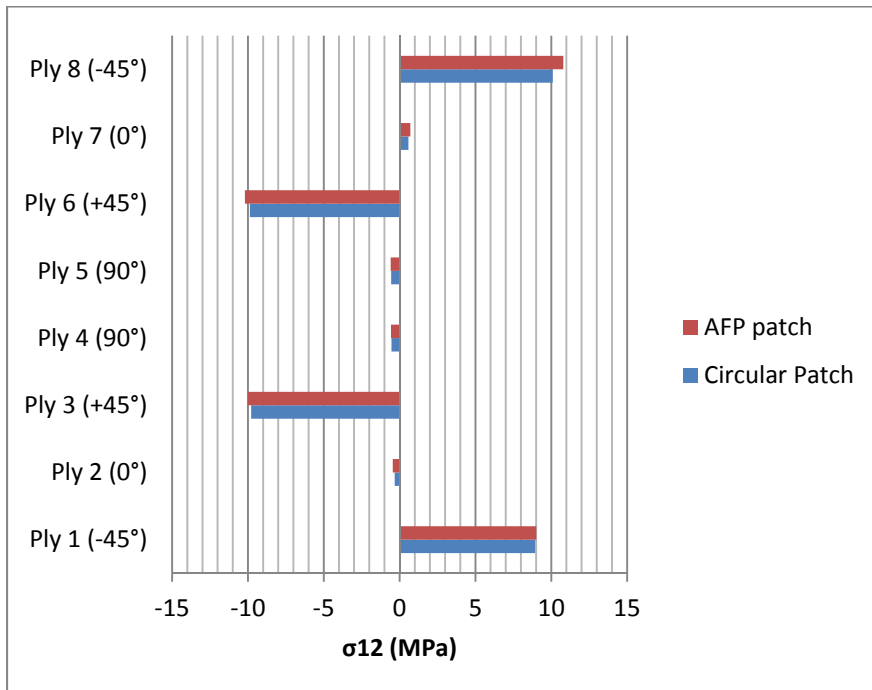


Figure 9: In-plane shear stress  $\sigma_{12}$  for traditional circular patch and AFP circular patch

### 3.2.2 Adhesive Layer and Adhesive/Adherent Interface

Figures 10, 11 and 12 show stresses  $\sigma_{11}$ ,  $\sigma_{22}$  and  $\sigma_{12}$  respectively in the adhesive layer for the circular patch and the AFP produced patch. Longitudinal stress  $\sigma_{11}$  and transverse stress values  $\sigma_{22}$  show high stress levels in the areas in line with the loading direction. Again, this agrees with elementary mechanics of composites principles. As shown in figure 10, longitudinal stress values  $\sigma_{11}$  for the AFP produced patch are higher by up to 6 % compared to the circular repair patch while transverse stress  $\sigma_{22}$  and shear stress  $\sigma_{12}$  show a significant increase by up to 26 % for the AFP produced patch as shown in figure 11 and figure 12 respectively. This may be due to the increased load transferred to the adhesive layer in the AFP produced patch. Indeed, design changes required to accommodate for the AFP method resulted in a larger volume for the adhesive layer causing the adhesive to carry more load.

Furthermore, shear stress in the adhesive layer between orthotropic laminates has been shown to create highly concentrated areas at the termination points of plies oriented in the main loading direction and across the thickness due to variation in ply properties in composite laminates [5]. This is further compounded when using the AFP method as ply drop-offs become critical areas due to the straight-edge cut of composite prepreg tape which can create stress concentration at tape edges as shown in figure 14. This phenomenon is particularly acute in the top plies and can be seen for longitudinal, transverse and shear stresses with maximum values seen at the edges of the adhesive where the top composite plies meet the adhesive layer.

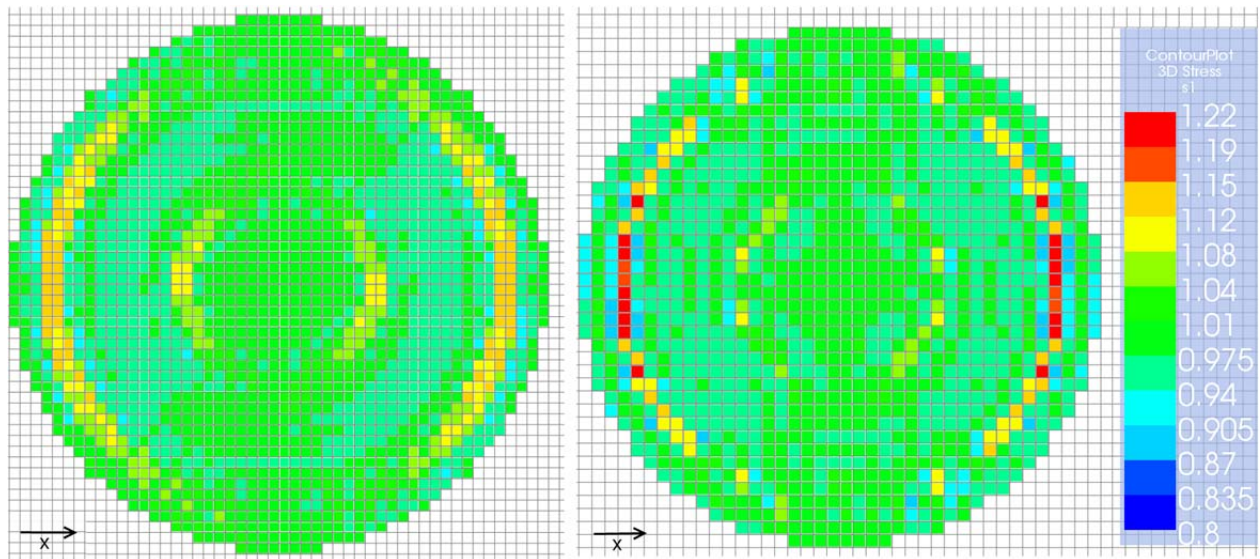


Figure 10:  $\sigma_{11}$  in the adhesive for circular repair patch (left) and AFP produced patch (right)

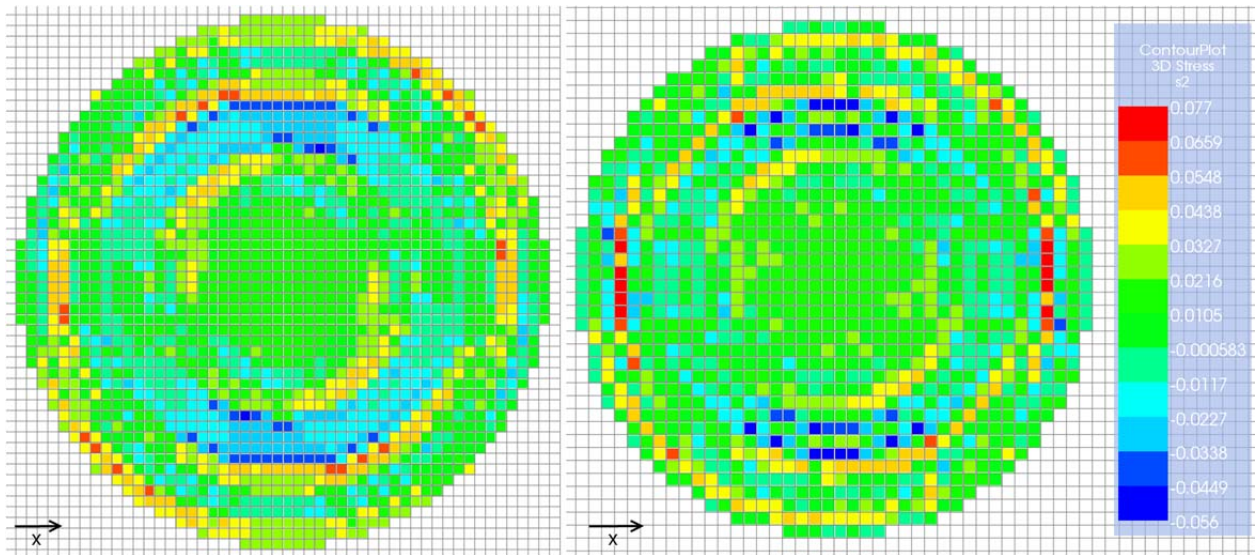


Figure 11:  $\sigma_{22}$  in the adhesive for circular repair patch (left) and AFP produced patch (right)

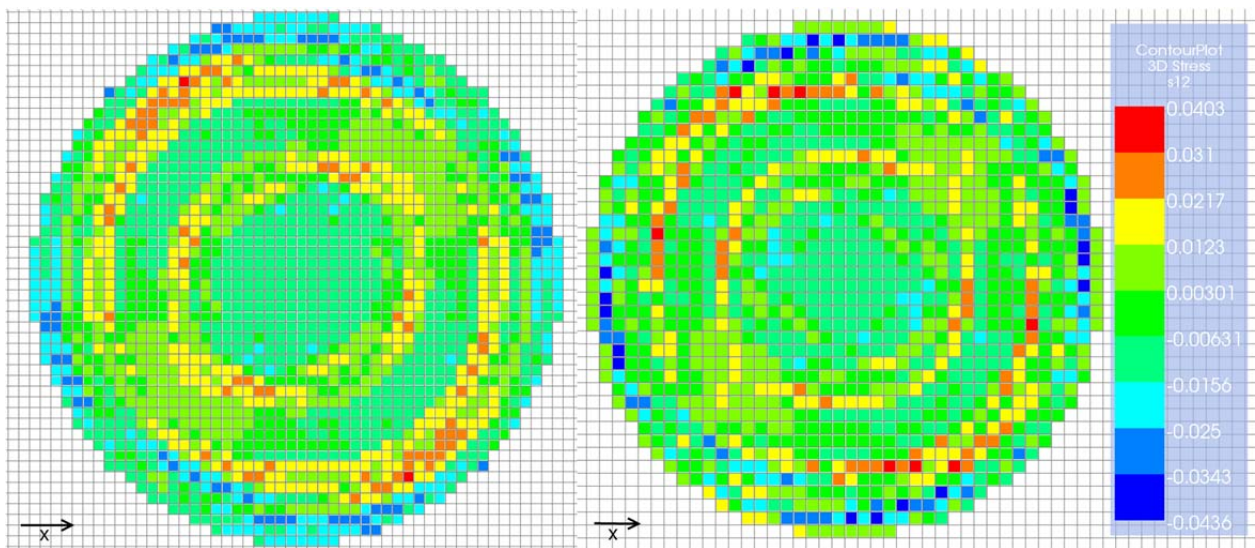


Figure 12:  $\sigma_{12}$  in the adhesive for circular repair patch (left) and AFP produced patch (right)

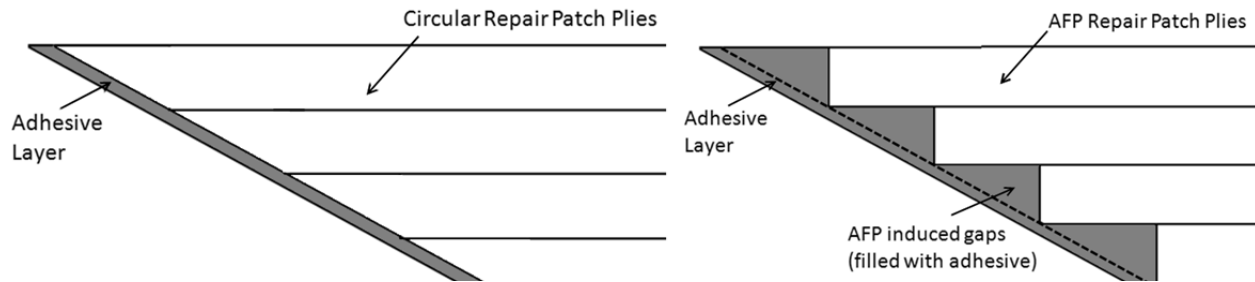


Figure 13: circular repair patch (left) and AFP repair patch layup (right)

#### 4. CONCLUSIONS

The presented work investigates the manufacturability of single-sided composite scarf repair patches using AFP. The damaged part consisted of a plate with dimensions 500 mm x 500 mm x 6.4 mm made up of 32 layers of AS4 3501-6 carbon/epoxy composite with layup  $[-45/0/45/90]_{S4}$ . The damaged area was scarfed with a taper ratio of 50:1. The repair patch consisted of an eight-layered quasi-isotropic repair patch  $[-45/0/45/90]_S$  and matched the parent structure ply-by-ply. The part was considered to be under an in-plane tensile load of 160 kN ( $\sigma = 50$  MPa). A simulation of the automated process for repair patch manufacturing was performed using Vericut Composites Programming (VCP) and a Finite Element (FE) model was built in ANSYS V14.5 to examine stresses in the circular repair patch.

The results show that repair patches made using AFP and traditional circular layers show similar stress fields across the repair patch laminate. This highlights that the resulting gaps filled with adhesive material that are created with an AFP produced patch have limited impact on the resulting stresses experienced in the repair patch. However, significant stress increase in transverse and shear stress were observed in the adhesive layer when using the AFP method. Indeed, design changes required to accommodate for AFP resulted in a larger volume for the adhesive layer causing the adhesive to carry more load. Also, ply drop-offs are critical areas due to the straight-edge cut of composite prepreg tape which can create stress concentration at tape edges. This phenomenon is particularly acute in the top plies and can be seen for longitudinal, transverse and shear stresses with maximum stress values seen at the edges of the adhesive where the top composite plies meet the adhesive layer.

The presented results show that the AFP method could potentially be a viable option for repair patch manufacturing but further work is needed to determine the impact of the increased stress levels seen in the adhesive. Also, the manufacturing of AFP produced composite repair patches depends heavily on the AFP head parameters and capabilities. The robustness of the AFP method applied to repair patch manufacturing and issues surrounding feasibility and implementation to a real structure will be the focus of future work.

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