EXPERIMENTAL STUDY OF COMPOSITE STRUCTURES REPAIRS USING ADDITIVE MANUFACTURING TECHNOLOGIES

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Abstract

The use of carbon fiber composite polymers (CFRP) in primary and secondary structures has shown enormous advantages for high performance aerospace applications for more than 40 years. A key factor of the development of these structures lies in their operational maintenance which, due to their high manufacturing costs, makes their repair indispensable if defects are detected (either during the manufacturing or during the operational life of the parts), then, avoiding the repetition of parts already manufactured. In this way, repairs have become a process of special importance in the aeronautical industry.

This study aims to establish a basis for a new automated repair system that improves the quality of the final parts and optimizes their cost, minimizing the time and material waste used in the development of repair patches. It is intended to develop a commercial system of additive manufacturing (AM), particularly the fused filament fabrication (FFF), to the repair of CFRP panels. To this end, panels have been manufactured with autoclave and have been repaired with this novel technique. In this study, several parameters have been considered to evaluate the mechanical behavior of the repair: stacking sequence of the laminate, the patch and base materials and the adhesive used to bond the patch. Experimental tests have been carried out to the panels with the purpose of obtaining a comparative analysis of their mechanical properties with respect to un-repaired parts.

From this work it can be extracted, that the repair with additive manufacturing allows mechanical performance of the original part to be recovered.

1. Introduction

Nowadays, carbon fiber reinforced polymers are widely used on airframe due to their extraordinary properties that have demonstrated weight, fuel and emissions reductions compared to traditional metallic airframe. Main aircraft manufacturers across the globe have included CFRP structures on their newest large passenger aircrafts, regional aircrafts and fast rotorcrafts. An iconic example of it is the Airbus A350 that present up to 50% use of CFRP in their structures [1]. Most of the CFRP airframes are manufactured by conventional methods such as autoclave curing, or more recently liquid resin infusion for Out of Autoclave curing processes. Key factors of these manufacturing processes are the raw material used, energy consumption, or lead times. Nowadays, the challenge is to increase the efficiency by improving these factors. With highly optimized manufacturing processes, aeronautical industry would incline even more to their use compared to metallic materials. Additive manufacturing (AM) technology applied for the manufacturing of CFRP can provide a solution for this, with high potential benefits for their manufacturing process.

Repairs of composite elements are very common in the aeronautical industry, especially when they are referred to minor accidental damages produced during operational life of aircrafts or defects caused during the manufacture of the parts. These repairs have a high impact on the maintenance cost of the aircraft, to achieve a repair process to reduce these costs being then a primary objective.

Though additive technology is not really a new concept (it appeared for the first time in 1986 [2], it is on the past few years when a few patented developments were released to public domain and their use has gone through an exponential rise. Therefore, the newness corresponds to the composite use as a raw material. AM counts with interesting advantages, such as high automation capabilities, possibility of manufacturing highly complex parts, low operational costs, energy consumption reduction, lead times reduction and raw material use optimization [3]. All this applied to composite materials can make the manufacturing process a disruptive key method for the enhancement of current aero-structures efficiency. For this study, an additive manufacturing process similar to FDM (Fused Deposition Modelling) has been used, but with the particularity previously mentioned of the raw material used: Nylon fibers in combination with thermoplastic polymer resin with the ability to cure out of autoclave.

The industry's main challenge is to increase the maturity level of CFRP produced by means of Additive Manufacturing and bring it closer to industrialization by producing repair patches of composite materials. For this purpose, a composite 3D printing equipment has been set up, several specimens including repair patches have been manufactured with AM, and various parameters have been comparatively analyzed (orientation of the laminate), patch material and base material, as well as the adhesive used to bond the patch, to evaluate mechanical behavior of the outcoming material. Tensile tests were selected as experimental method to carry out the comparative study in terms of mechanical properties of the various repaired configurations.

The tasks developed in this study are the description of tests carried out and characteristics of test samples to be tested. Subsequently, manufacturing of repaired panels with ALM patches is detailed. Finally, the most important results and conclusions are extracted from the tests.

2. Tests and coupons description

A repair has the objective of recovering a damaged structure to an acceptable level in terms of hardness, durability, rigidity and performance of the part [4]. Before to start a repair, it is important to establish some details of the repair procedure, such as a damage assessment, the selection of a repair criterion, the selection of suitable materials and the processes to be carried out, specifying the area and size of the repair. The most common technique to perform the repair is by means of patches. For the development of this study, step sanded repair methodology has been chosen to perform adhesive repairs (see Figure 1) [4]. The patches studied have been manufactured with a 3D printer. The joints between panels and patches have been carried out with two bonding materials, film adhesive and two-phase adhesive.

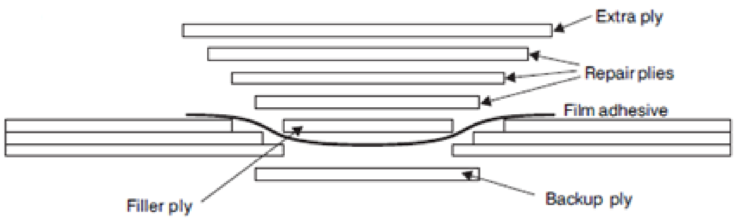

Figure 1. Stepped repair [4]

Staggered panels composed of six layers of pre-preg carbon fiber AS4/8552 in unidirectional tape have been manufactured. The defect included is to be repaired with the patch manufactured on the 3D printer.

Two different reinforcement materials have been used to manufacture the repair patches using the 3D printer, specifically carbon fiber and fiberglass, both materials being compatible with Mark One Printer® and supplied by MarkForged [5]. In the same way, different adhesives to join the panel with the patch were studied; film adhesive (Z-15429) [6] and two-phases adhesive (B017966, Redux - 30065M -40M2/PK).

Tensile tests have been performed in order to obtain a comparative analysis of the behavior of repaired panels by additive manufacturing technology, and also to make a comparison between repaired panels and unrepaired panels [7].

3. Coupons manufacturing

In this section, the manufacturing process of the carbon fiber panels with defects, the repair patches manufactured by 3D printer, and the repair process of the panels will be described.

- <u>Manufacturing of carbon fiber panels with defects:</u>

It is necessary to manufacture carbon fiber panels with stepped geometry to be repaired later with patches made in a 3D printer. In order to avoid including more variables in the analysis of the repair behavior, the panels have been manufactured directly with a staggered geometry, avoiding sand processes (Figure 3).

A total of six panels were manufactured, where four of these six panels were manufactured with the fibers on the direction of the longest dimension of the panel (0º) (Figure 3a) and the other two panels with the fibers oriented to the shortest dimension of the panel (90º) (Figure 3b). This distribution of panels can be observed in Table 1. The geometry of the panels is shown in Figure 3. In order to achieve the required steps configuration, rectangles of different dimensions were cut from the pre-preg and stacked in a specific sequence. Subsequently, these panels were cured in an autoclave following its corresponding cure cycle.

Figure 2. Carbon fiber panels with defects

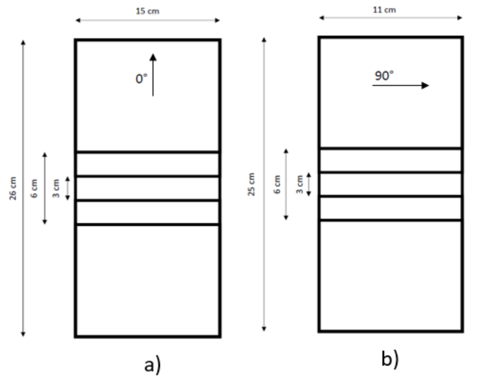

Figure 3. Geometrical dimensions of panels

Table 1 Summary of panels manufacturing

	Panel material	Panel Orientation	Material to be repaired	Patch Orientation
Conf1	Carbon fiber	90º	Carbon fiber	90º
Conf2	Carbon fiber	90º	Carbon fiber	90º
Conf3	Carbon fiber	0º	Fiberglass	0º
Conf4	Carbon fiber	0º	Fiberglass	0º
Conf5	Carbon fiber	90º	Fiberglass	90º
Conf6	Carbon fiber	90º	Fiberglass	90º

- Repair patches:

Fiberglass patches and carbon fiber patches were manufactured. The fiberglass patches have a 0° and 90° orientation and those of carbon only 90° orientation. Some limitations appeared during the manufacturing process of the carbon fiber patch. It was found that the orientation of the fiber can not be customized, as the deposition of the fiber is done circumferentially and in the central zone includes nylon [8]. The part model geometry introduced in the printing software has to fit into this constrain. To obtain a patch of this material, the panel that can be printed must be machined, as shown in Figure 4. In this way, the carbon fiber patch is obtained in two parts that will later be bonded together.

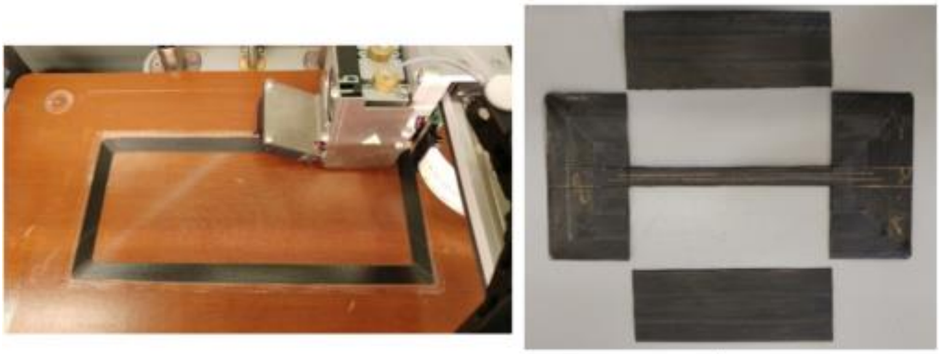

Figure 4. Carbon fiber patch manufacturing

- Patches bonding

Several configurations were manufactured based on different parameters such as orientation of the layers, type of repair patch material and adhesive used. The configurations are shown in Table 2.

Table 2. Configurations manufactured

	Conf1	Conf2	Conf3	Conf4	Conf5	Conf6
Carbon Fiber	90º	90º	-	-	-	-
Fiberglass	-	-	0º	0º	90º	90º
Adhesive	Film	Two phase	Two phase	Film	Film	Two phase

The bonding of the specimens were carried out as secondary bonding, i.e., both the base and the patch material were cured before bonding. In order to improve the joint, the adherents were previously sanded. Film adhesive was cured at 120ºC, since two phase adhesive was cured at 60ºC. The bonding of the fiberglass patches lacked complexity, not occurring this way for carbon fiber patches, where it was necessary to take special care in the alignment since they were formed by two halves. For all configurations, tabs were bonded by adhesive redux with the purpose of promoting valid failure modes on the central areas of the specimens.

The different configurations of repaired panels are shown in Figure 5 - Figure 10.

Figure 5. Conf1 Carbon fiber_90º (film adhesive)

Figure 6. Conf2 Carbon fiber_0º (two phases adhesive)

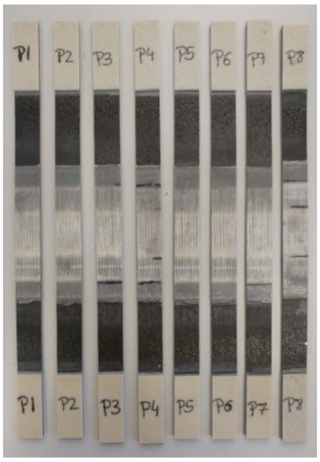

Figure 7. Conf3 Fiberglass_ 0º (two phases adhesive)

Figure 8. Conf4 Fiberglass_0º (film adhesive)

Figure 9. Conf5 Fiberglass_ 90º (film adhesive)

Figure 10. Conf6 Fiberglass_90º (two phases adhesive)

4. Test Results

The manufactured specimens can be divided into two main groups: those whose repair has been manufactured with fiberglass and those that have been repaired with carbon fiber. In the case of fiberglass, there are two orientations of the repair fibers (0° and 90°). However, only the test specimens with 0° repair patch are tested because the specimens manufactured with 90° orientation presented a significant curvature (see Figure 11), as a result of the residual stresses to which the fibers were subjected during path curing. These residual stresses are caused by the joining of two different materials with different thermal expansion coefficients in a curing process that involves high temperatures. Two types of different adhesives have been used, and 5 repaired specimens of each series were extracted and tested.

Table 3. Tests results

Patch material	Orientation	Adhesive	Tensile Strength (MPa)	DST (%)
Fiberglass	0º	Film	500.55	6.09
Fiberglass	0º	Two phases	354.64	4.43
Carbon Fiber	90º	Film	30.00	4.21
Carbon Fiber	90º	Two phases	17.57	17.57

Figure 11. Excessive curvature in Fiberglass patch at 90º

The test results obtained during the test campaign are shown in Figure 12 - Figure 15. A higher tensile strength can be observed in specimens repaired with film adhesive, due to the fact that a film adhesive achieves a better distribution of stresses throughout the patch. On the other hand, elastic moduli are similar for each type of patch (fiberglass and carbon fiber), since this property is mainly controlled by the substrate panel, equal in both cases.

Initially, fiberglass patches curves present a linear evolution until the patch contribution appears, where the specimen leaves its linear behavior. In the case of carbon fiber patches, curves only present a linear evolution up to failure, due to the fact that the stacking sequence of specimen is equal to 90º, and the resin is the most important factor associated with the tensile strength.

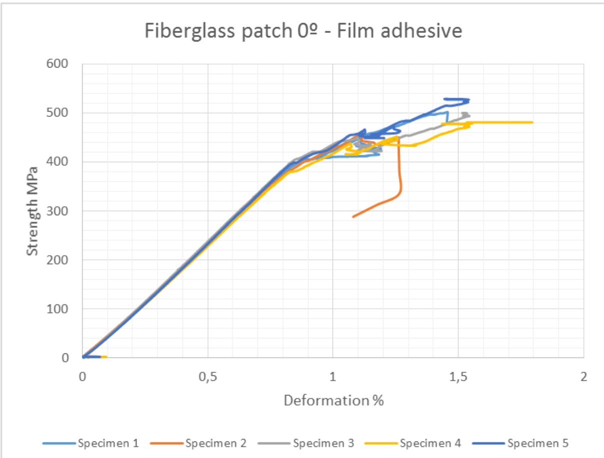

Figure 12. Fiberglass patch 0º - Film adhesive

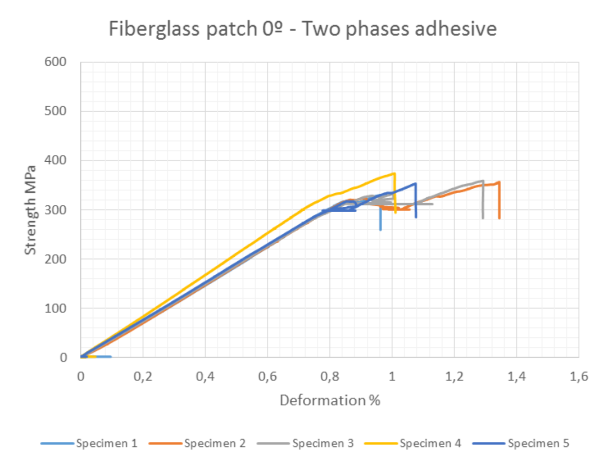

Figure 13. Fiberglass patch 0º - Two phases adhesive

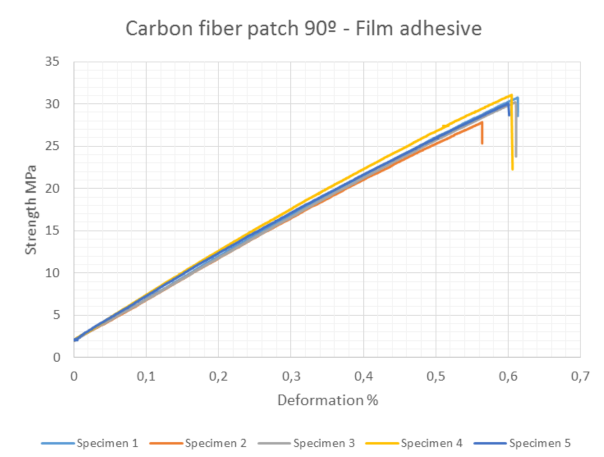

Figure 14. Carbon fiber patch 90º - Film adhesive

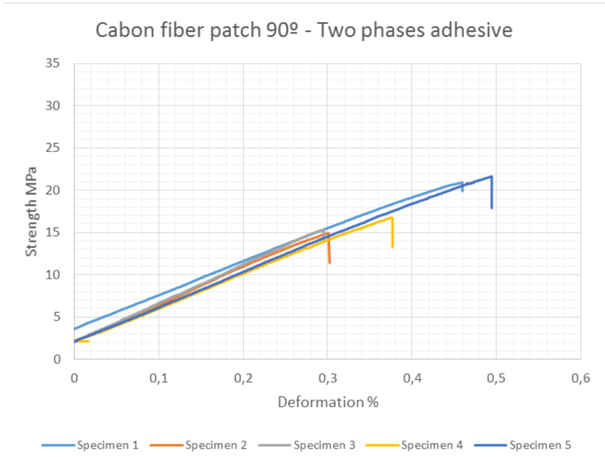

Figure 15. Carbon fiber patch 90º - Two phases adhesive

5. Discussion

With reference to the comparison of results for specimens repaired with carbon fiber patch and oriented 90º, according to Figure 16, those repaired using AM technology have a lower tensile strength than those repaired using a conventional procedure. This result is a consequence of a repair process by AM due to the fact that this is a technology that needs to be optimized, particularly for carbon fiber, where 90º repaired specimens present a discontinuity in the repair patch that can favor an undesired premature failure. However, the results are more promising when using adhesive film during the joining process, obtaining approximately 55% of the tensile strength of specimens repaired using a conventional procedure with adhesive film.

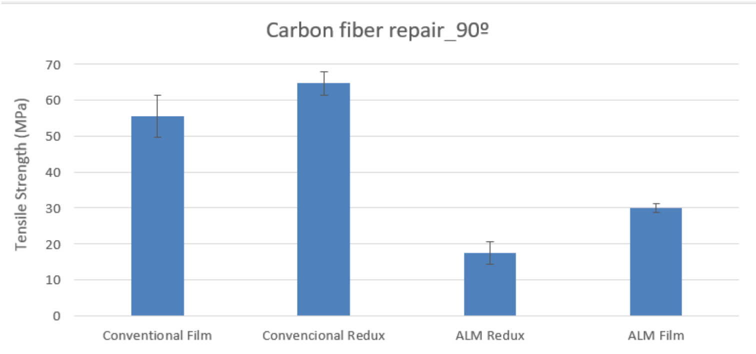

Figure 16. Comparison of the tensile strengths obtained with the different types of repair

Figure 17 summarizes results with the purpose of comparing the influence of the fiberglass patches oriented at 0°. It shows that the presence of a fiberglass patch does not improve the properties with respect to the staggered specimen without repair. In fact, tensile properties decrease. These results are caused by the residual stresses that appear in the repair patch when it is subjected to the curing process, due to the fact that the fiberglass has a thermal expansion coefficient different that carbon fiber coefficient. This confirms that the patch and base materials are key factor for the success of the repair. The repair patch shall be of the same material (or similar thermal expansion coefficient) as the base material in order to recover the mechanical properties of the original specimen. Although this result was expected by the fact of using different materials, the aim of these trials was to study the viability of repairs performed with patches manufactured by additive manufacturing technology.

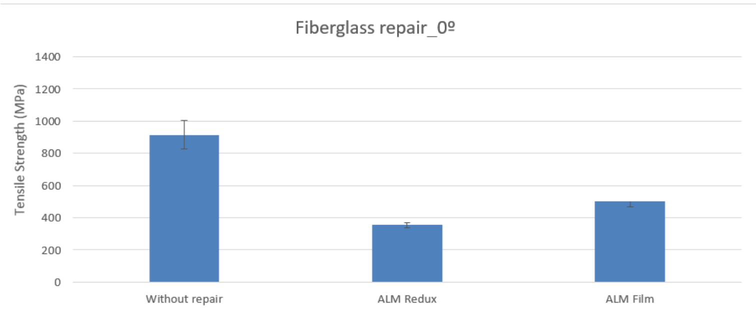

Figure 17. Influence of the fiberglass patch

6. Conclusions and future work

Repairs of carbon fiber reinforced panels with patches manufactured by additive technology has been carried out, using two types of materials (carbon fiber and fiberglass). Main objectives have been reached, as hopeful results have been obtained, and these results should improve considerably for future high maturity levels of the technology. Furthermore, basis for additive manufacturing CFRP repairs have been established. Nevertheless, it presents certain limitations such as the possibility of manufacturing patches in carbon fiber with different orientations. Solving this technical limitation would enable a more exhaustive study where patches with different carbon orientations must be deeply studied.

Despite additive manufacturing advantages, we must be realistic with the maturity of these technologies. At the present time, additive manufacturing technology is being adopted by different sectors such aeronautic or automotive. This study allows the foundations to achieve and implement the technology in composite repairs in aeronautical industry to be settled.

It is strongly believed that, with a small tuning of the actual additive manufacturing process relate to the ability of the equipment to print in different orientations, much better results will be enabled, even reaching similar performances to those observed in repaired patches using conventional methods.

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