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INVESTIGATION OF A COMPOSITE REPAIR METHOD BY LIQUID RESIN INFUSION

M. Hautier, D. Lévêque, C. Huchette, P. Olivier*
ONERA, DMSC
29 av. de la Division Leclerc, 92322 Chatillon, France
*Université de Toulouse, UPS, IUT P. Sabatier, IGM-LGMT Dépt. GMP –
133C av. de Rangueil, B.P. 67701 – 31077 Toulouse CEDEX 4, France
mathieu.hautier@onera.fr

SUMMARY

“Conventional” repair procedures for impacted composite structures (i.e. patches) are time-consuming, and must be performed by highly qualified staff. In this paper a cost-effective and simple repair method by liquid resin infiltration is studied. The liquid resin is used to fill in the damaged region organized as a crack network.

Keywords: Composite Repair, Liquid Resin Infusion, Crack, Delamination, Impact Damage

INTRODUCTION

Nowadays airlines are bidding on composite materials for their high specific mechanical performances. However, those materials are well known for being very impact-sensitive. Damage resulting from a low velocity impact on a monolithic composite structure have been widely studied and are now well described [1]. Nevertheless, the repair of these damage can still be considered as an issue. Conventional and certified repair procedures do exist but require highly qualified staff (mandatory), specific equipments and remain time-consuming. For these reasons, we focused our research work on settling a faster, cost-effective and simpler repair procedure. Such solutions (*i.e.* filling-in the impact-induced damaged region by a liquid resin) have been first studied in the beginning of the 90’s for repairing composite laminates [2]. It has also been shown that polymer infiltration enables to slow down and repair fatigue cracks in composites [3]. As this kind of repair is not used at an industrial scale further explorations needed to be made.

In order to establish this worthiness, several steps have been performed: (i) composite damage identification, (ii) repair method definition, (iii) mechanical validation.

COMPOSITE DAMAGES

The origins of damage in composites are numerous but all composite manufacturers and users do agree on their impact sensitivity. Composite designs are meant to undertake static loads and ageing effect, but accidental solicitations are difficult to predict and are more likely to damage composite structure. Those extraordinary solicitations (chocks during assembly process, hail impacts, tools impacts…) can occur during fabrication, assembly or lifetime. Airbus and Boeing [4-5] assume that low energy impact is the most frequent damage origin.

Therefore the detection of such damage and their repair is of great interest. Plenty of methods do exist and even more are being developed. Quasi-isotropic laminates are the most used stacking sequence and the damage induced by an impact is very specific. It is organized in delaminations with a conical double helix shape connected with some transverse cracks in the plies (Figure 1). The size of the damage grows from the impact side to the rear side. Generally for low energy impact there is very little fibre breakage.

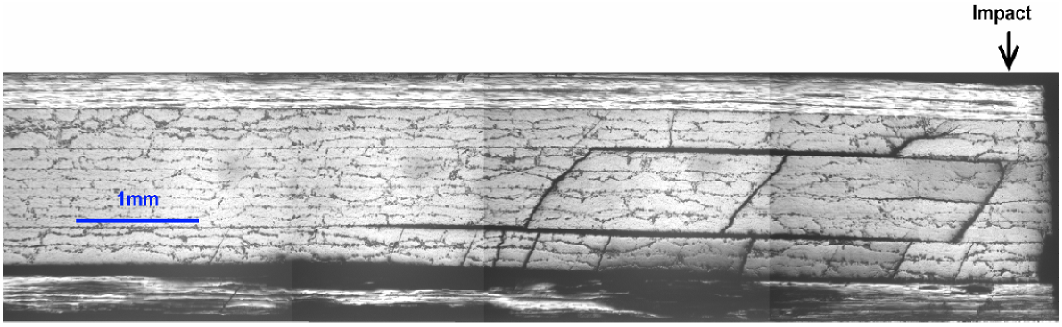

Figure 1: Impact Damage with delaminations between plies and transverse cracks on a $[0_2/+60_2/-60_2]s$ laminate.

REPAIR METHODS

Composites and more precisely carbon/epoxy composites have now been in use for over 40 years and from that time, investigations have been made on their repair methods [6]. Aeronautical composites structures are usually repaired with metallic or composite patches. They can be bolted, riveted or bonded [7]. Unfortunately most of the existing processes do not take into account the specificities of composites like the anisotropic properties. On composite structure the repair process with a composite patch is time consuming and needs a well-trained work force. It consists in cutting out some sane fibres even if, the damage is not of very big extent and the fibres breakage is low.

INFILTRATION METHOD

The repair proposed in this study is based on liquid resin infiltration. The principle of the method based on [2] is presented on Figure 2. The goal is to make the resin flow from one side of the part to the other by filling all the cracks and delaminations. This repair does not apply to all damage and is specific to low energy impact damage, which is the most common damage encountered in aeronautics. This smart repair focuses on the only real damage in those composites that is matrix cracks. Because repairs are generally not convenient, another goal of the proposed repair was to use as few materials as possible available in maintenance centres.

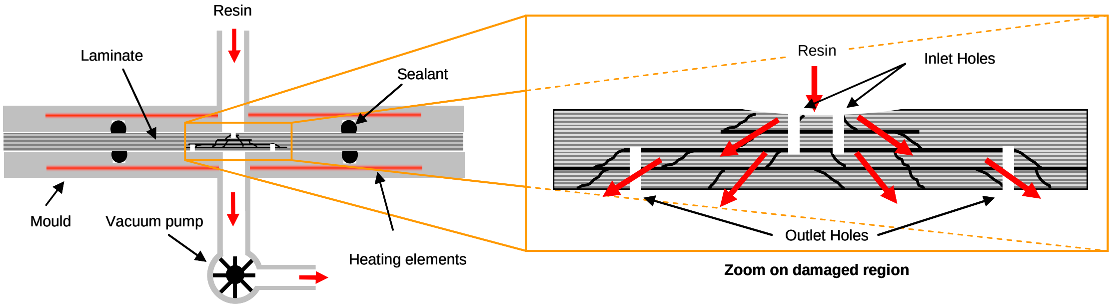

Figure 2: Principle of the infiltration method

The repair process follows several steps: i) Material preparation; ii) Pre-heat of the repair components; iii) Vacuum of the repair system; iv) Resin flows through the part; v) Cure; vi) Surface treatment if needed.

The material preparation is the standard preparation with damage identification and cleaning. Holes drilling which is also part of the preparation, is the only none obvious operation because the 1mm holes mustn't be drilled through the entire part but only half way through. This enables the resin to reach easily the delaminations and cracks even if the crack net doesn't lead naturally to the top surface. As the repair is meant to be processed on various stacking sequences, a ring shape of holes is defined for the resin inlet and outlet. The number of holes depends on the orientation of the plies and the diameter of the ring is set with the damage extent. A physico-chemical investigation presented below ensures a good penetration of the resin. After preparation, heating is then not always necessary and depends on the resin used. On the contrary, vacuum is a critical stage. It ensures the good penetration of the resin in cracks and combined to heating it enables to extract some pollutants (water, acetone …) which can be introduced during the preparation phase. The influence of an additional injection pressure has also been studied.

More numerical work and experiences are being done to evaluate the possible mechanical strength diminution due to the inlet and outlet holes. This configuration of holes is challenging because so small holes aren't usually studied and the fact that the holes do not lead to both sides of the part creates dissymmetry and instability especially in compression.

PHYSICO-CHEMICAL INVESTIGATION

It was important to make sure that the resin could flow properly in very small spaces such as cracks in composites. This development is in phase with the recent developments on Resin Transfer Molding (RTM) resins. Those resins do need to have a very low viscosity, good glass transition temperature and good mechanical properties. A great importance has been accorded to the resin toughness properties because it seems to be the best parameter to describe the quality of a repair. One of the best resins that could be found meeting those characteristics was the RTM6 and has been selected for this study (Table 1). This table presents also the material selected for this study (T700GC/M21) with high strength carbon fibres and a third generation toughened epoxy resin used on the A380 aircraft.

Table 1: Material Properties

Materials	Minimum Viscosity	Toughness (J/m²)	
		mode I	mode II
T700GC/M21 (UD laminate)	10 Pa.s	350	1200-1400
RTM6 (resin)	50 mPa.s	168	1000

In order to simulate the resin flow in cracks it was decided to use an analytical model. Before finding the depth reached by the resin during repair process, it was necessary to make sure that viscosity effects wouldn't interfere. From Darcy's law we get the time, t, of infiltration by:

$$t = \int_0^L \frac{2 \cdot \eta \cdot x}{\mathrm{K}(x) \cdot \Delta P} dx$$

where L is the delamination length, η the resin viscosity. K is the delamination permeability given by $K = h^2(x)/12$, ΔP is the pressure difference between the injection pressure and the pressure in the none injected zone. For simplification purpose, the cracks and specially delaminations were considered as triangular with a maximum thickness of 20µm. From this equation the infiltration time was evaluated to less than 10 seconds. The viscosity used for calculation is η = 50mPa.s and the delamination length L = 20mm. As the resin stays at low viscosity for about 10 minutes we considered that time was not a problem to infiltrate our longest delamination.

The second step consisted in knowing how close to crack tip the resin could go. The pressure equilibrium enables to find the theoretical resin front position:

$$P_I + P_C = P_R$$

In which P_I is the injection pressure, P_R the residual pressure in the zone not yet injected and P_C the capillary pressure given by:

$$P_C = \gamma\left(\frac{2\cos\theta}{h(x)} + \frac{1}{x}\right)$$

Where γ is the surface tension of the resin, θ the contact angle between the resin and the material to be repaired and h(x), the thickness of the delamination depending on the position x. This capillarity term shows that the materials combination is essential. Those values have been determined experimentally to ensure that the material combination chosen for the repair was satisfying. Those measurements were done under the same temperature and material roughness than during the repair process and we obtained a contact angle of maximum 45° and a surface tension of $32 mJ/m^2$. The infiltration simulations finally gave a penetration rate of more than 99% for our configuration (size of delamination, materials…)

MECHANICAL CHARACTERIZATION

In order to demonstrate the repair process worthiness, some mechanical testing was necessary. The easiest way to test a repair is a structural test in which damage can be created and repaired. As the Compression After Impact test is one of the most common and discriminating test on composites structures we naturally oriented the mechanical testing on this method. Nevertheless for understanding purpose it was also interesting to investigate some fracture mechanics tests in order to test the repaired interface by itself.

COMPRESSION AFTER IMPACT TEST (CAI)

We have chosen the compression after impact test developed by Boeing as structural test because it is considered in aeronautics as one of the most discriminating test for composites. It is also particularly well adapted to repair evaluation. The complex boundary condition with the anti buckling fixture is meant to simulate the behaviour of panels between stiffeners on an aircraft structures. The tests were performed on undamaged, damaged and repaired samples.

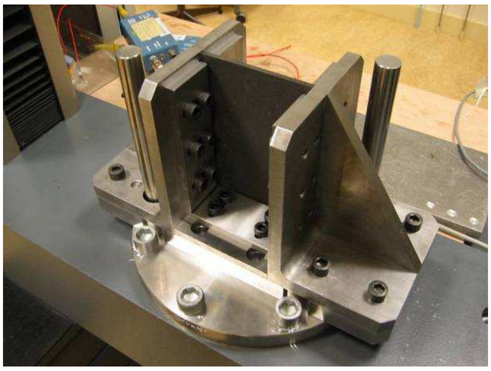

Figure 3: Compression After Impact test fixture

The geometry of the sample and the test procedure are given by the standard ASTM D7136 and ASTM D7137. The quasi-isotropic stacking sequence selected for this study is: $[0°_2/+60°_2/-60°_2]_s$. Quasi-static indentations on a circular window have been preferred to impacts in order to produce the most reproducible damage. Ultrasonic inspection Figure 4 and micrographic cuts confirmed the good concordance between quasi-static indentations and low velocity/low energy impacts (same general shape and depth of delaminations and same transverse cracks rate).

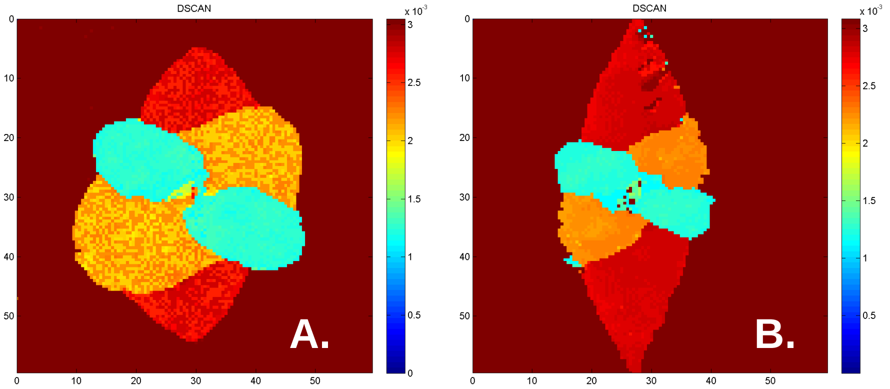

Figure 4: Ultrasonic inspection of a $[0°_2/+60°_2/-60°_2]_s$ laminate damaged by: A. quasi static indentation; B. 16 Joules impact

In order to follow the spoiling of the sample during compression test, a 3D image correlation system was used. Global buckling was observed on the undamaged and repaired samples whereas a local buckling was observed on the damaged samples. No significant compression modulus difference was observed between undamaged and repaired samples. Concerning the ultimate compression strength good results were achieved regarding the relative 'poor' quality of the infiltrated resin. As shown on Figure 5 the repaired samples do recover at least 90% of the ultimate strength.

The influence of the injection pressure on the quality of the repair was also investigated. As we suspected in the resin development, the injection pressure seems to mostly influence the infiltration time. The difference in ultimate compression strength of the repaired samples with or without pressure is not significant regarding the dispersion of compression tests.

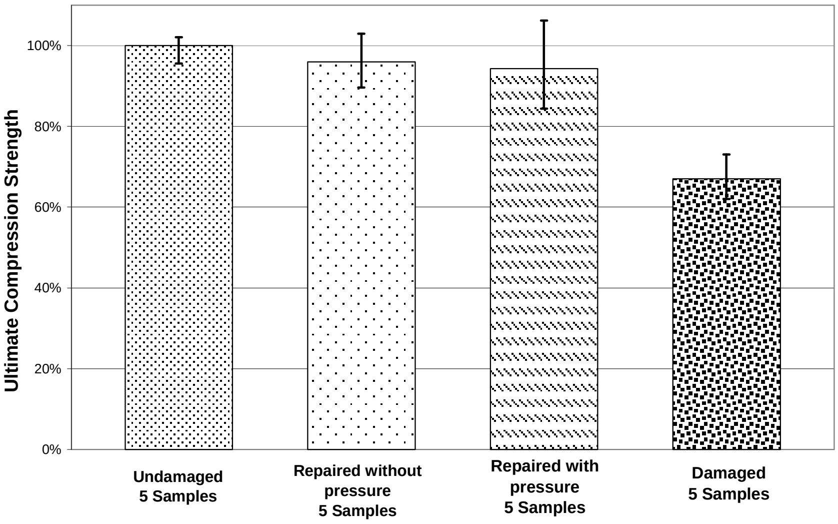

Figure 5: CAI results on undamaged, repaired and damaged samples (mean normalized strength and min/max values).

ELEMENTARY TESTS

As the resin injected has much lower toughness properties than the original material and that we did restore most of the compression properties of the samples tested in CAI, further exploration needed to be done in fracture mechanics. Double Cantilever Beam (DCB) test and End Notch Fixture (ENF) test have been chosen to qualify the repair capability of the resin in mode I and II (Figure 6). Both tests have been investigated with a sane and a repaired interface.

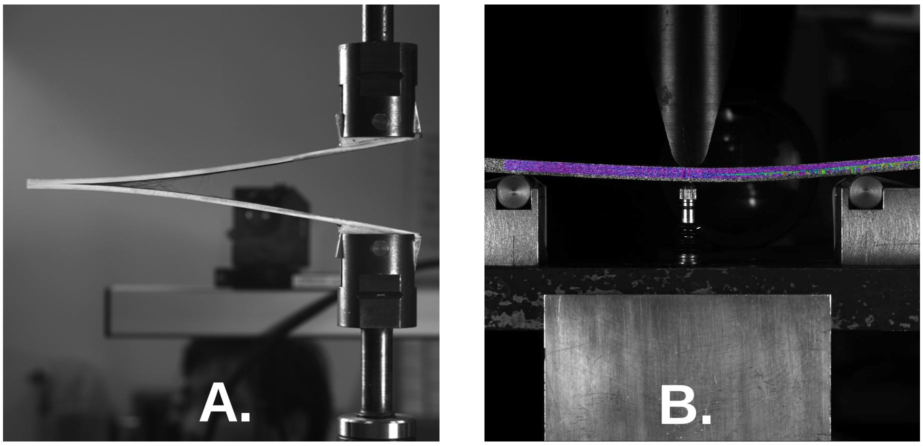

Figure 6: A. Double Cantilever Beam test; B. End Notched Fixture test

Even if those tests are quite simple, manufacturing the repaired samples was not obvious as we wanted to stick to the repair process. In impact induced damage the delaminated interfaces is rough. In order to reproduce this kind of interface, a large panel of T700GC/M21 UD laminate ([0°$_8$//0°$_8$]) was opened in mode I and repaired with the RTM6 resin. The disoriented and loose fibres where removed to minimize the thickness of the repaired interface. The different samples were then cut up for the elementary tests.

DCB test (mode I)

As it can be found in the literature [8], composites do follow an R-curve chart type. This is due to fibre bridges virtually which increase the energy necessary to propagate the crack. Initial and propagation values of the sane samples of T700GC/M21 are in accordance with what can be found on this particular material [9].

In the repaired samples, all the bridges due to the in-thickness miss-alignment have been destroyed in the repair process. This explains the relatively constant energy rate for all the repaired samples. We can observe on Figure 7, that with RTM6 repair resin we do not resituate the initial properties of the T700GC/M21 (see **Table 1**). However, it seems that the repair is at least as good as the repair resin and with a better repair resin we should get a better behaviour in DCB test.

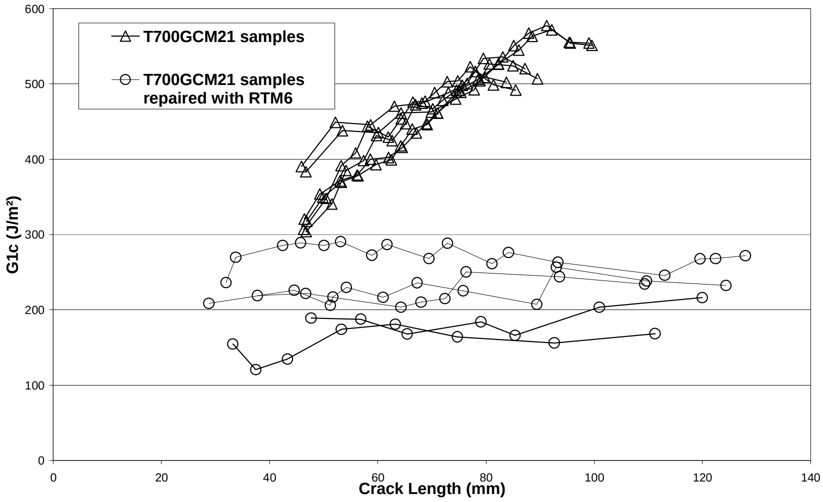

Figure 7: DCB results on T700GC/M21, sane and repaired with RTM6 resin

ENF test (mode II)

The ENF test has been chosen upon many other mode II tests because it is pretty simple and gives relatively good results. This test is based on a 3 point bending test on a pre-cracked sample in order to generate shear stress near the crack tip. In order to have even more stable values the crack tip is placed at 70% of the support span and the imposed displacement is stopped at the first maximum load. The sample is then completely unloaded and the crack tip is re-placed at 70% of the support span. The crack tip never reaches the region below the central punch.

As for the DCB results, the repaired samples do not reach the values of the sane T700GC/M21 samples Figure 8 but compared to the values found in the literature for RTM6 system by itself, the repair seems again to be at the maximum capacity of what can deliver this epoxy resin [10].

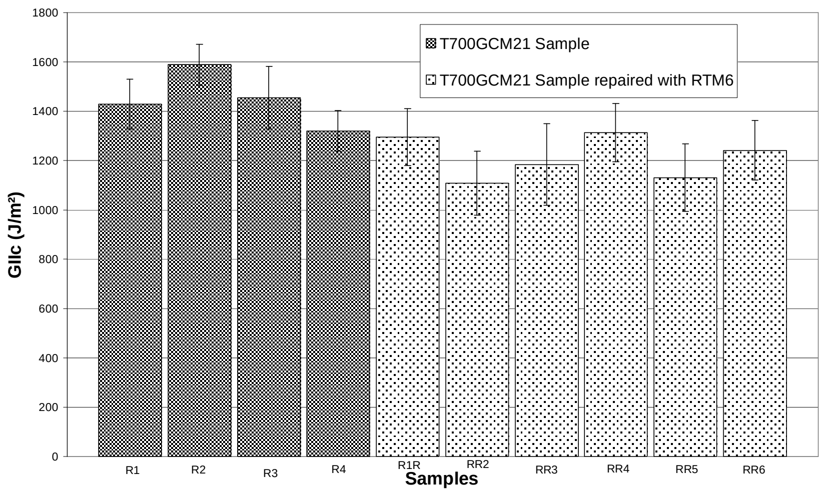

Figure 8: ENF test results on T700GC/M21; sane and repaired samples with RTM6 resin

Conclusion on elementary tests

In both mode I and II we did recover the toughness of the repair resin. This is very encouraging and with the recent developments of new matrix systems it is very likely that we could restore the initial toughness properties of the T700GC/M21 which is one of the best thermosets that is certified nowadays in aeronautics.

In the tests realized it seems that the cohesion of the repair resin was lower than the adhesion between the cured epoxy and the repair resin. This adhesion strength could be a limit with the increase of the materials toughness specially to withstand better impacts.

CONCLUDING REMARKS

From the information collected in various composite industries, no new repair methods have been developed and used for composite's repair at industrial scale. The existing repairs are immoderate regarding the most common damage: low energy impact damage. The repair investigated in this study is specific to this kind of damage. With the available resins, it seems difficult to restore the toughness properties of toughened systems but recent new resin developments do give hope of accomplishing the restoration of such properties. Meanwhile the results obtained in CAI tests are very encouraging. The restitution of nearly the entire initial compression strength shows that toughness is not the only criteria for achieving a good repair. Other 'structural' solicitation must be investigated to qualify this repair technique. However more investigations must be done on that repair and especially because of the reduction of immobilization time and cost are worthy.

There is still some understanding on the behaviour of repaired interface in order to validate the process and have this repair fly. Numerical developments can be of good help for this understanding and hopefully predict the strength of such repairs.

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