STUDY OF DOUBLE STEP LAP COMPOSITE REPAIRS ON CFRP EVALUATORS

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Abstract
An innovative repair process and evaluation are proposed. Firstly, the originality of this work consists on the process used for the repair milling: an Abrasive Water-Jet milling. A double-step lap coupon is chosen to demonstrate the feasibility of the milling process. This specimen is made of M10.1/38%/UD300 CHS 460 from Hexcel Composites. After milling, the removed material is reconstructed laying up the same prepreg material with a one-ply shift in the staking sequence. A Redux 609 adhesive film is used to ensure a correct bonding on the interface. Secondly, the originality concerns the mechanical characterization of the repair quality assessed through an innovative multi-axial mechanical test. It allows to choose multi-axial loadings according to the requirement. The selected test is a combined bending and compression test. Finally, results of mechanical tests are presented and discussed.

1 Introduction
With the continuous growth of composite materials use in transportation, the repair process of large primary composite parts becomes crucial for maintenance. For economic and technical reasons, the replacement of a whole part could be difficult, or even impossible for principal structures, so the damaged parts must be repaired. These repaired structures need to be as safe as the original for the same life-cycle.
Research on repairs using composite patches began 40 years ago. Initially, composite patches were used to repair some metallic structures, but researches have been focused on repair of composite structures since 10 years.
Two types of repairs are principally investigated. “Cosmetic” repairs are used to re-create the shape of the part to be flush, but not to restore mechanical strengths [5]. The second type of repairs is the structural repairs which are employed to reconstruct the material in order to give the same life cycle as the original one.
For a structural repair, the first step requires to remove the damaged material. Two shapes for material removal are noted: scarf repairs [1-2-3], and step-lap repairs [4]. Nevertheless, Step-lap machining is more difficult to obtain with the classical milling techniques, and most papers focus on scarf optimization, on the patch shape or on the stacking strategy.
In order to study the feasibility of step-lap machining, Jedo Technologies, in collaboration with the Clement Ader Institute and Composites Expertise and Solutions, has developed a composite milling process based on the relevance of the Abrasive Water-Jet Milling (AWJ) [6-7]. This contribution presents a demonstration of the ability of such process to prepare

structural parts for repairing. Indeed, the AWJ permits to remove composite material ply-by-ply, and offers the capability to perform step-lap shapes, even for curved surfaces [7]. In this study, a double step lap shape is milled by means of this process, to simulate a repair machining.

In the first part of this report, the selected part is presented, which is called evaluator. The repair process is then described. An original modular multi-axial testing machine used for mechanical tests is introduced, and the numerical models in order to design the mechanical test for a chosen localization and nature of damage are explained. Finally, results of chosen mechanical tests are presented and discussed.

2 Geometry of the evaluator

To demonstrate the ability of AWJ to perform repair machining, a particular evaluator for composite repairs has been designed. For possible comparison between classical milling technique and AWJ, this first evaluator presented in this paper is designed as a plane laminated plate. This evaluator has to be representative of structural parts, thus dimensions have been chosen to be larger than those of elementary coupons. It is made from 16 M10.1/38%/UD300 CHS 460 plies provided by the Hexcel Company, with a quasi-isotropic stacking sequence. The laminated plate is approximately 5.2 mm thick. The length of the coupon is determined using the capacity of the multi-axial testing machine, in this case is 600 mm. The width is set to 130 mm.

Once plates are stacked and cured using a classic curing cycle in autoclave (3h00 at 180°C), an AWJ milling is performed to simulate a repair machining. The milled shape is a double step-lap shape as shown in Fig. 1.

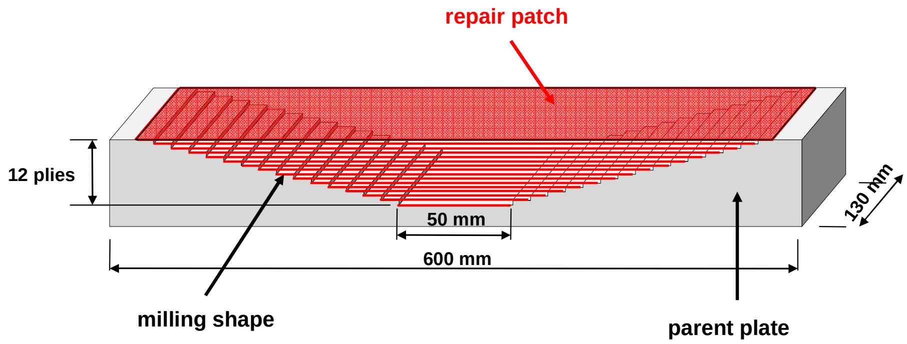


Figure 1. Coupon geometry and milling shape.

Assuming that the damage is localized in the upper skin of the plate, the four lower plies are supposed to be undamaged and are therefore not machined. Steps are symmetric towards the 50 mm central zone. Each step is straight and parallel to the width of the plate. They are 9 mm long and have the same thickness than the ply (i.e. ~ 0.32 mm). The ability of the AWJ machining to reach the interface between two adjacent plies is useful to address various reparation processes and test different configurations (See Fig. 2). The AWJ process used for this machining is not described in this paper. For more information, one could refer to [6-7].

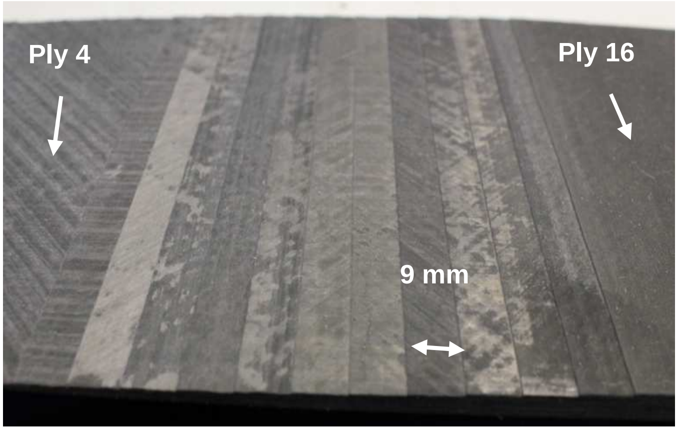


Figure 2. Steps machined with Abrasive Water-Jet Milling.

3 Repair process

The selected repair strategy attempts to take profit from the ability of the AWJ to reach the interfaces between two adjacent plies. The assumption is that the loading transfer could be optimized if the parent ply and the patch ply around each step have the same orientation (See Fig. 3). The patch's material is the same as the parent plate one. An adhesive film is used to ensure a structural bounding between parent plate and the patch. The adhesive is selected to be compatible with the temperature curing cycle of the patch's plies, being the Redux 609 provided by the Hexcel Company.

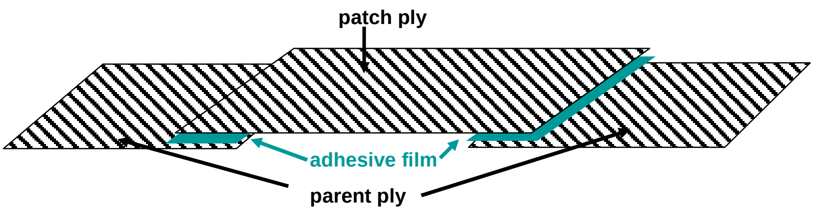


Figure 3. Repair strategy with the overlapping of two plies with the same fiber direction bonded thanks to structural adhesive.

The repair process consists in stacking the patch plies ply by ply before curing. The first step is laid on the adhesive film in the parent plate (in blue in Fig. 4), after decontamination of the surface. Once the adhesive film is laid, the patch plies are stacked, beginning by the smallest placed at the center of the repair (See Fig. 4). Every four plies, the evaluator are placed in a vacuum bag for compaction. After the stacking process of the patch, the repair evaluators are placed under heating mats, and then inside a vacuum bag. Both adhesive film and patch are cured at 180°C during 3 hours.

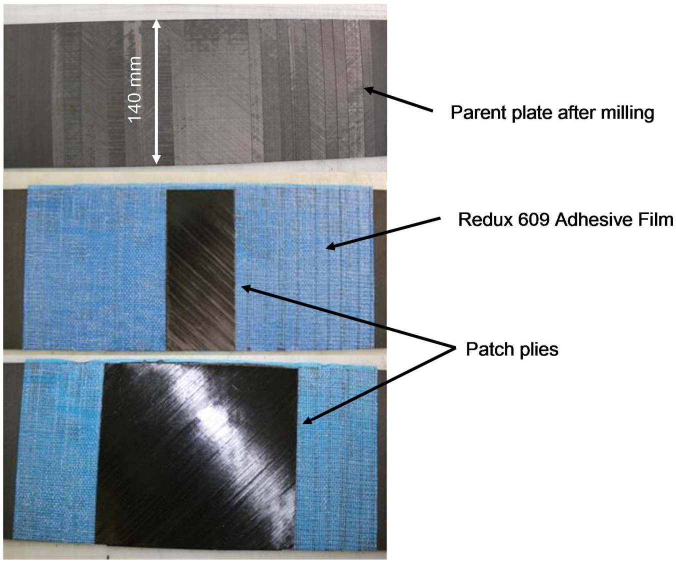


Figure 4. Lay up process for the repair patch with upper (before repairing) and middle and bottom (two different phases of the stacking process).

4 The Multi-instrumented Technological Evaluator tool box

The Multi-instrumented Technological Evaluator (MITE) toolbox is conceived to study composite structures [8, 9, 10]. The MITE toolbox is composed for its experimental part by an original multi-axial testing machine to test the composite structure. It allows the use of various instrumentation methods thanks to the size of the evaluator. The numerical part of the MITE tool box consists in a set of numerical tools to conceive the test with a loop of optimization and to analyze the experimental tests.

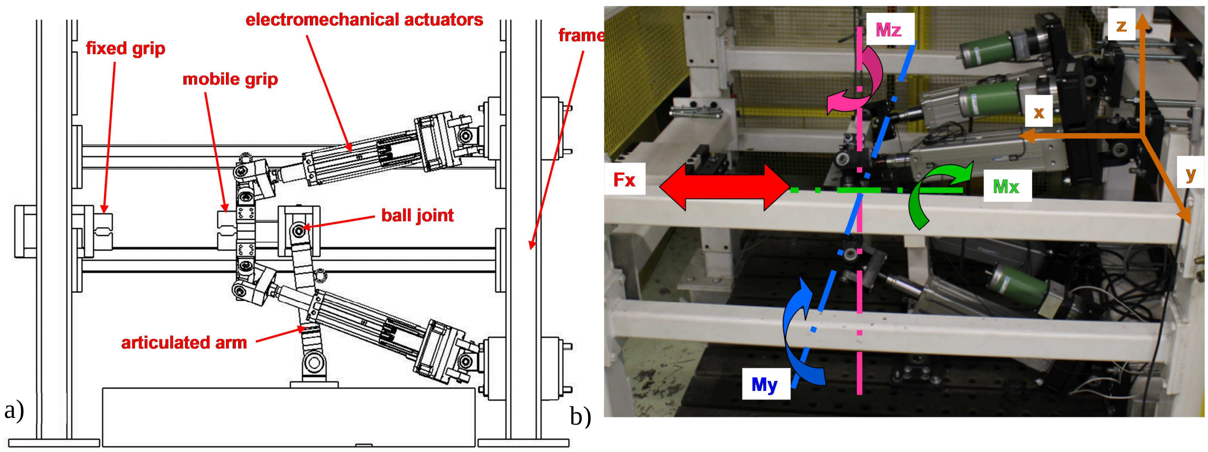


Figure 5. Experimental part of the MITE Tool box with a) drawing of the Multi-axial testing machine and b) available multi axial loadings provided by the testing machine.

The experimental set up consists in a multi-axial testing machine composed by 4 electromechanical actuators articulated at their attachment to the frame on one side. In their other extremity, the actuators are attached to a steel rectangle (See Fig. 5.a). The independently movements of the four actuators permit to obtain four elementary displacements and solicitations: tension/compression (Fx along the X axis, see Fig. 5.b), and three torques around the X, Y and Z axis. An articulated arm is used to forbid displacement along the Y and Z axes. The evaluators are fixed to the rectangle on one side and to the frame in the other side. Each actuator has the possibility to be driven separately to obtain any combinations of each elementary movement. This offers the possibility to place composite evaluators in a multiaxial state of stresses, which are representative of stresses chosen and/or encountered during the service life of a structural part.

In the current configuration of the MITE modular testing machine, the maximal dimensions of the coupons are 600 mm long and 300 mm width. The maximum loads are approximately 140 kN in traction and compression, 8 kN.m of torsion moment around X, 30 kN.m of bending moment around Y, and 40 kN.m of bending moment around Z. If the axial load available is at a usual level to the one in the standard testing machines, the additional bending moments available offer a very huge capacity. This permits to test parts with a representative thicknesses of the ones used in aeronautical structures.

5 Numerical design of the mechanical test thanks to MITE toolbox

Each mechanical test assessed by the MITE approach is designed by means of simple FE models (2D).

The mechanical tests on repaired coupons presented in this paper are designed using the Samcef Finite Element software. The model used is a 2D composite model representing a healthy plate, assuming that repaired plates have to reach the same mechanical behavior as the healthy one. The 2D model is chosen due to the necessity of perform several calculations to optimize the loads trajectory and the geometry of the coupons. In the MITE approach, the loading and the geometry of the specimen need to be designed simultaneously, this leads to perform several iterations to ensure that the stress state corresponds to the **desired** one.

The selected mechanical tests to asses the quality of structural repairs are characterized by a combination of bending and compression. This choice leads to a restrictive stress state at the interface of the repair patch: a mix of in-plane shear stress and out of plane tensile stress inside the interface, and mixed compressive and tensile stresses in the patch, depending on the position in the thickness.

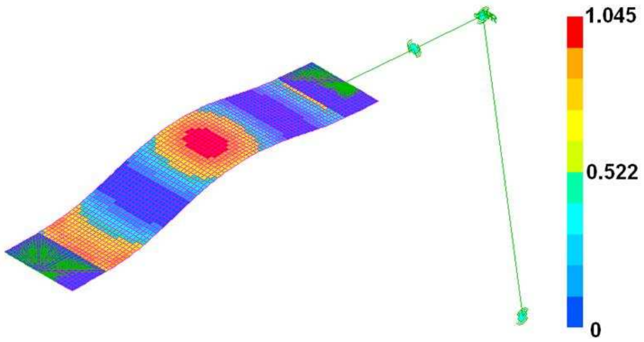


Figure 6. View of Tsai-Hill criterion for a 2D FE modeling in the inner 0° plies at the end of the test.

The numerical calculi lead to a 5° flexure and 12 mm compression test for the chosen target. Indeed using these boundary conditions, the most stressed zone of the healthy plate is localized at the center of the plate, which is also the location of the maximal thickness of the repair patch. The plate is computed to reach the failure of the inner 0° ply, in compression (See Fig. 6). Loads and displacements are checked to be compatible with the capabilities of the multi-axial testing machine.

6 Experimental results

Evaluators are prepared for mechanical tests by bonding strain gages to assess the strain variation in various places of the coupon during the tests, and attaching the supports for the grips at the extremities of the coupon (See Fig. 7). These grips are designed to transfer the loads to the coupon, particularly to bending and flexural moments. They present a variable thickness to avoid stress concentration. They are designed to be easily mold employing the HexTOOL® M61, whose stiffness is similar to that of the coupon.

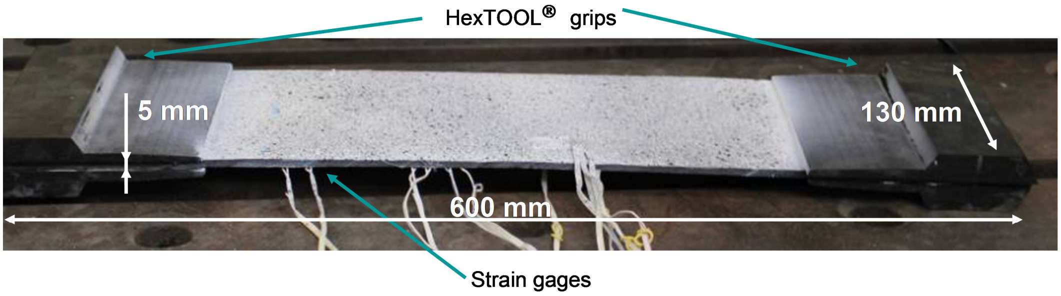


Figure 7. Repair evaluator with its multi-instrumentation (MITE) ready for mechanical tests.

Once the evaluators are equipped with the strain gages and the grips, they are tested in the multi-axial testing machine (See Fig. 8). Deformation shape and the global behavior are close to the predicted one by FE methods. Final loads are 10% higher than predicted. Nevertheless, the ultimate failure is far from the predicted one in terms of displacements: the repair plate breaks after a 20 mm compressive displacements, while the 2-D numerical simulation predicted 12 mm of compressive displacements.

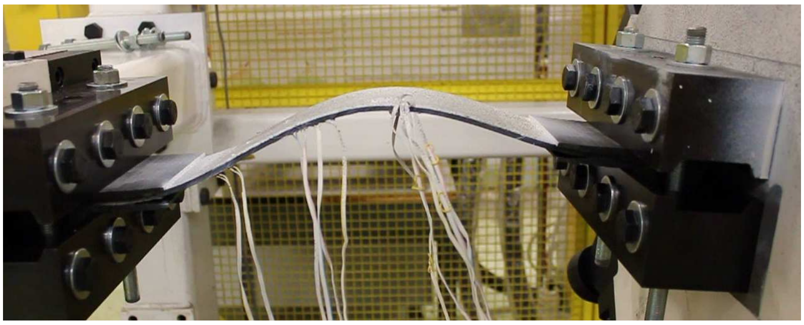


Figure 8. Deformed shape of repair evaluator just before final collapse.

To evaluate the quality of the repair, a healthy plate (called “reference plate”) with the same dimensions and materials, is produced and then tested with the same mechanical loadings. Global behavior is comparable between the repaired plate and the reference plate. One can note that final loads are higher for the repaired plate (See table 1). This result is mainly due to the different thickness of the plates: the reference plate has a stacking sequence of 16 plies, while the repaired plates have 17 plies. The additional ply is the result of the repair strategy selected. Moreover, the repair patch is cured inside a vacuum bag, and not in an autoclave. This leads to different volume fiber ratio and ply thickness. Nevertheless, results show that the repair process seems to be acceptable, and permits to retrieve the mechanical properties of the parent plate.

	Reference plate	Repaired plate
Compressive loading component (kN)	11.7	13.6

Table 1. Comparison of compressive loading at collapse level between reference and repair evaluators.

The fracture modes seem to be different between repaired plate and reference plate. In the first case, fracture is meanly characterized by the ejection of the repair patch (See Fig. 9), revealing the milling shape, and the adhesive film (in blue). In the case of the reference plate, the fracture does not represent a global failure of the plate, but occurred by the brittle behavior of the inner 0° plies. This zone in the middle of the plate was subjected to an important compression state.

Nevertheless, a careful observation of the broken repaired plate leads to the conclusion that all inner plies are also broken. At this stage of the study, one can make the assumption that, for the repaired plate, the inner 0° plies could have broken in compression first. A shock wave is then transferred immediately to the rest of the coupon, thus ejecting the patch. This assumption needs to be confirmed by finer FE simulations or by using a high-speed camera during further tests.

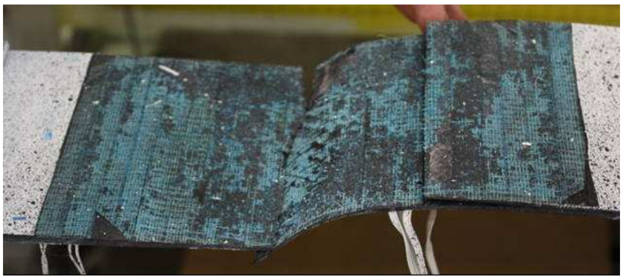
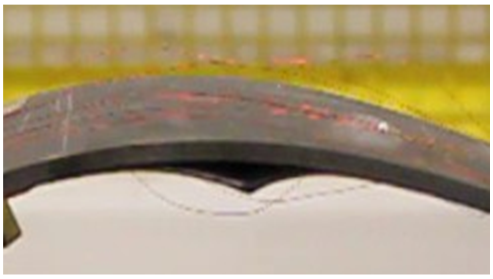
a)  b) 

Figure 9. Views of rupture facies with a) debonding of the repair patch and collapse of the inner ply of the parent part and b) fracture of 0° plies in the inner face of the reference plate.

7 Conclusions

This study demonstrates that AWJ machining could be a possible method to prepare the repair of structural composite parts. Due to the ability of AWJ to remove ply-by-ply the composite, it permits to imagine new repair strategies which are difficult to obtain by classical machining. A bending – compression mechanical test showed that a plane repair evaluator in the described and chosen strategy can reach its initial mechanical properties with in a multiaxial stress-state.

This study is a first step towards a complete evaluation of repairs obtained by AWJ machining. It has to be completed with more experiences to confirm results presented here. Additionally mechanical tests are being implemented using the capacity of the modular multi-axial testing machine to apply different sets of loadings to confirm the quality of the reparation, e.g. the same mechanical tests as presented in this paper, but with the patch located at the bottom face.

Finally, the mechanical tests could be modeled employing numerical methods to increase the understanding of phenomena involved in the test. The second aim of the numerical studies is to increase the capacity to predict the behavior of a structural repair, and in a future being able to optimize the repair of principal primary structures.

A new generation of repair MITE is proposed [10] to address issues coming from primary principal composite structure on the very strategic subject of "on field" large repairs of primary principal structures for composites (as fuselage or wing).

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