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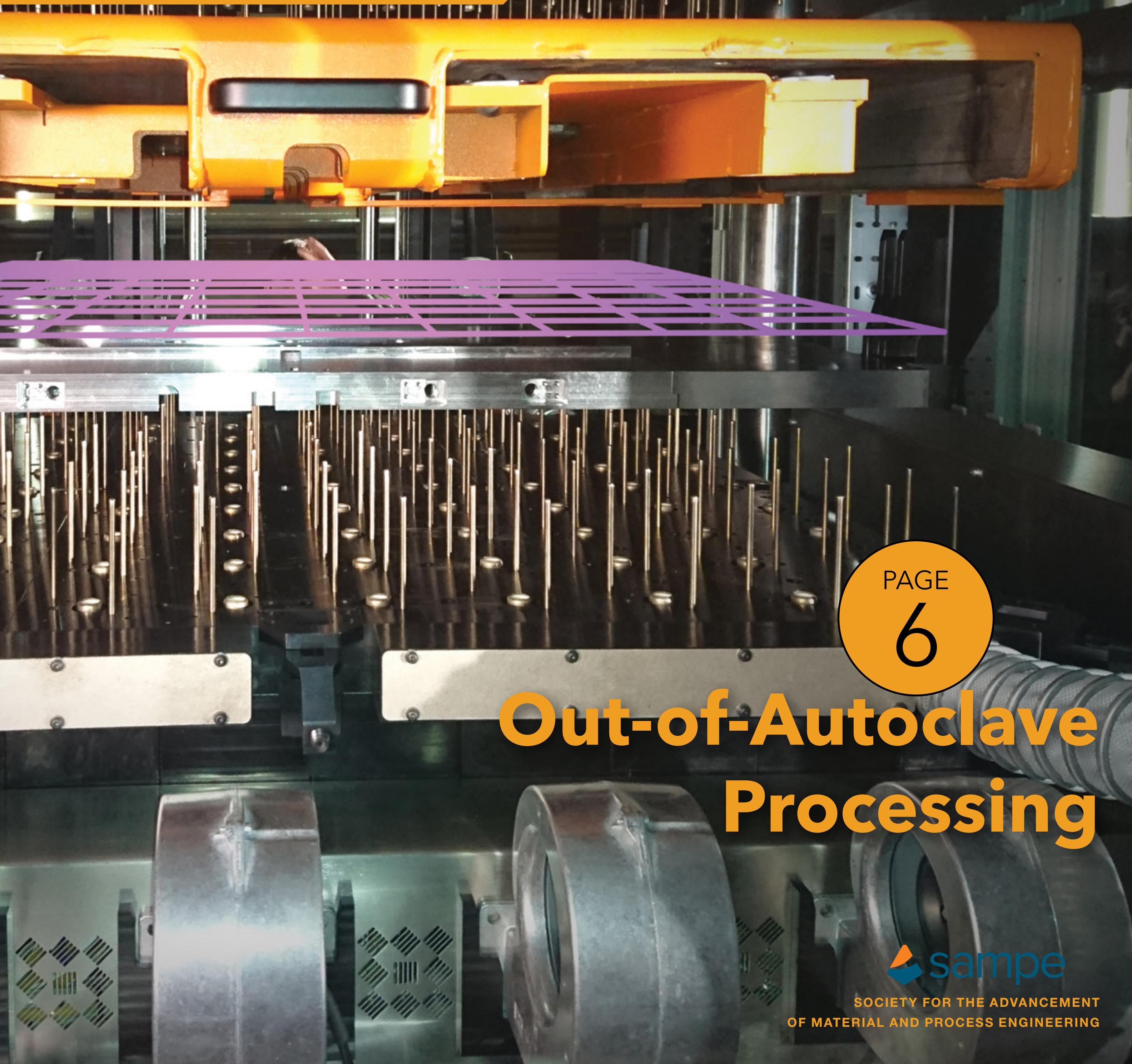
SAMPE JOURNAL | JULY/AUGUST 2020



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Out-of-Autoclave Processing

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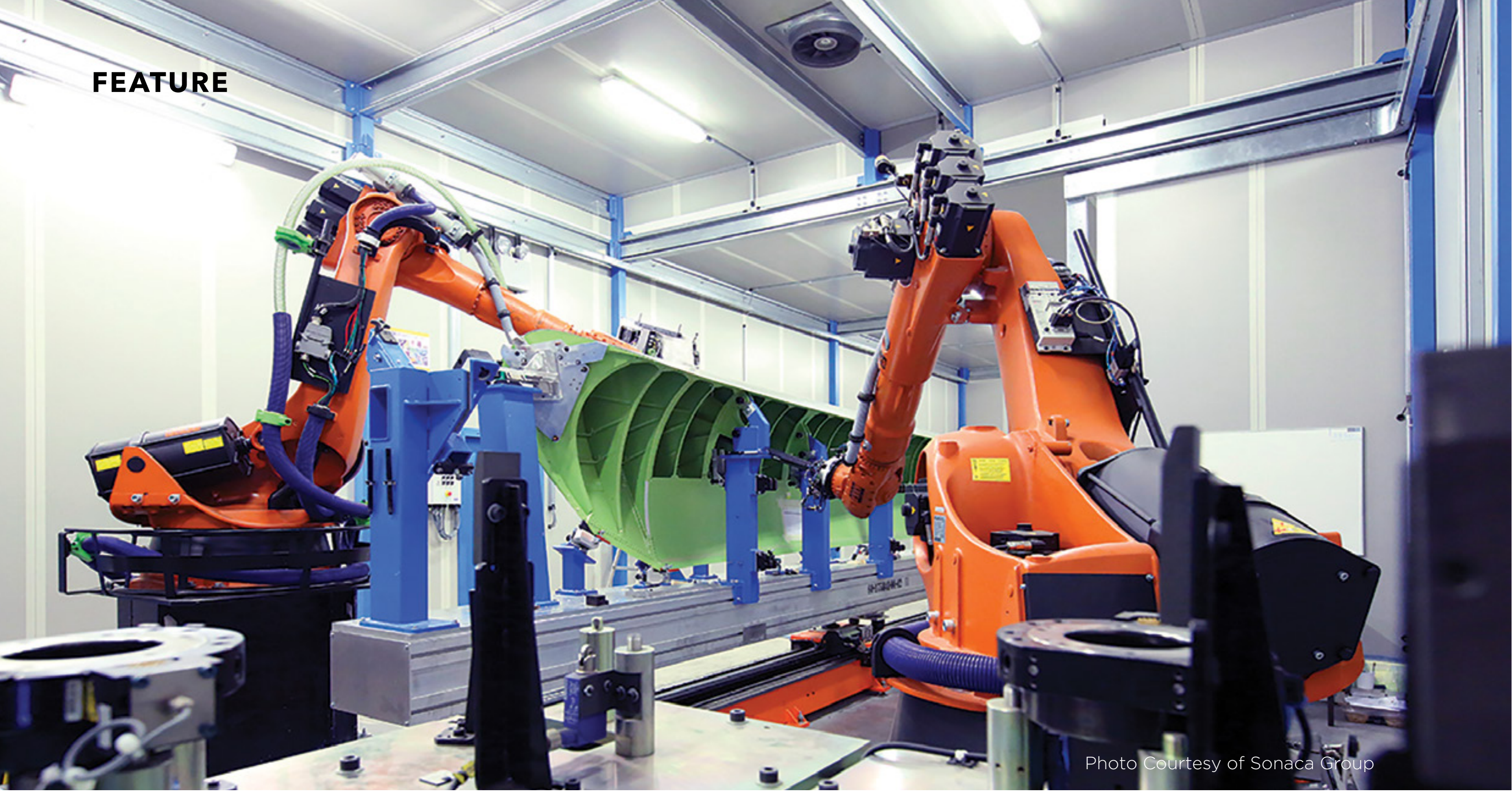

Photo Courtesy of Sonaca Group

COMPOSITE WING MOVEABLES

Out-of-Autoclave Process and Automation: A Successful Path to Highly Integrated and Cost Efficient Composite Wing Moveables

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ABSTRACT

With the continuous growth of the aviation market, it is mandatory to have manufacturing processes that allow for cost reduction, high production rate and high performance structures enabling reduction of fuel consumption and CO2 emission.

To that end, lots of out-of-autoclave technologies have been developed worldwide in the past years (RTM, VARTM, LRTM, VARI, RFI, etc.) but only SQRTM (Same Qualified Resin Transfer Molding) enables to combine a good control of process key parameters (volume content, pressure, thickness, temperature) from closed mold capability and the use of high tough qualified prepregs. Starting the development of SQRTM in 2010, SONACA was the first European company to introduce SQRTM in serial production with the flaps of the Embraer E2 regional jets family.

Since then, the company has pushed the technology further, combining it with automation, and has recently produced, first time right, a series of composite front & rear wing moveables with a very high level of structural and functional integration, achieving high cost reduction and performance.

Comparing SQRTM to autoclave and RTM, the paper will demonstrate the gains achieved by SQRTM, combined with automation and integration, through the recent manufacturing of several full-scale wing moveables demonstrators, mechanical validations and economic analysis.

INTRODUCTION

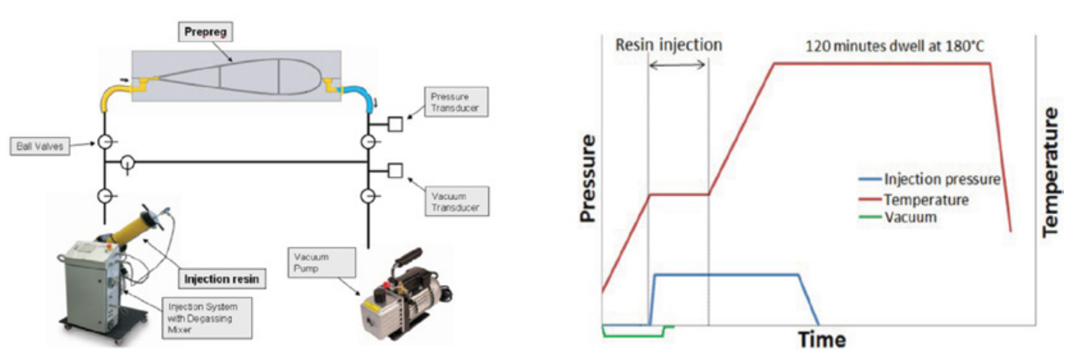
The developments of manufacturing technologies for aerostructures are driven by high performance, cost reduction and high production rate. A large variety of composite manufacturing processes have been developed to compete with metallic technologies. Epoxy- based prepreg materials cured in autoclave were first introduced in significant amount on aircraft for their high strength to weight ratio. In order to reduce the sensitivity of composite structures to impact, tough epoxy resin containing thermoplastic fillers were developed. This search for tough resins made prepreg technologies more suitable than injection/infusion processes. These processes require resins with a low viscosity in order to let the resin impregnate the dry fibers preform. A second development route was to reduce the manufacturing cycle and cost of the composite structures. Different means have been developed. One is automation such as Automated Tape Lay-up and Automated Fiber Placement to reduce the lay-up cycle time. Another mean is the development of out-of-autoclave processes. A large number of out-of- autoclave processes have been developed, mainly combined with dry preforms (RTM, VARTM, LRTM, VARI, RFI, etc)[1-2]. The use in serial production of processes combining dry preforms and injection/infusion has been limited so far, due to the less performant materials (generally, less tough than prepreg) and the low maturity of automated equipment for plies lay-up. Some prepreg materials cured under vacuum only have also been developed but this process route highly depends on the lay-out of the ancillary materials to create some channels and let the volatiles flow out of the laminate during curing. With this kind of technology, the vacuum bag preparation is more complex and the curing process is less robust. An alternative of using prepreg without autoclave, while keeping the process robust, is to cure the prepreg in a closed mold with pressure applied by an ancillary resin (the same as the prepreg resin) injected along the edges of the part. This last process is called SQRTM (Same Qualified Resin Transfer Molding). It has been initially developed by Radius Engineering Inc. and SONACA was the first European company to introduce SQRTM in serial production with the flaps of the Embraer E2 regional jets family.

Another way forward to manufacture structures with high performance and cost reduction has been to take benefit of composite technologies to increase the parts integration and reduce the number of curing and assembly steps. While prepreg materials, cured in autoclave, are limited to parts with low integration such as fuselage or wing panels, closed mold processes such as RTM and SQRTM are well adapted for complex parts with a high level of integration[3-4]. However, SQRTM is the only one to allow for parts integration with a good control of process key parameters (volume content, pressure, thickness, temperature) from closed mold capability and the use of high tough qualified prepregs. Moreover, by using conventional prepreg materials, SQRTM can be combined with all existing automated lay-up processes (ATL, AFP). Based on this rationale, SONACA has launched a vast development program in 2010 to develop SQRTM combined with automation and has produced a series of composite front & rear wing moveables with a very high level of structural and functional integration.

SQRTM PRINCIPLE AND COMPARISON TO AUTOCLAVE, RTM AND VACUUM ONLY PROCESSES

SQRTM process consists in curing prepreg material in a closed mold. The pressure inside the mold is applied by a small quantity of prepreg resin that is injected to fill the tool cavity around the edges of the part and maintain pressure until the gel of the prepreg material. The heating profile and pressure

Figure 1. SQRTM process principle and typical curing cycle.



range of the SQRTM injection/curing cycle are typically within the current process specifications of OEMs. The injection system and press equipment are similar to those used for RTM. SQRTM is compatible with both UD and woven reinforcements and all qualified prepregs (ex: 8552, 977-2, M21E, 3900-2, BMI 5250-4) as long as the resin of the prepreg (or almost equivalent resin) is available in bulk or unreinforced film form. This is the case for the resins mentioned previously. There is no material qualification needed and the existing material allowables (from autoclave curing) can be used. Mechanical tests on coupons (lamina and laminate properties) have shown the material properties equivalency between autoclave and SQRTM curing[5]. The only qualification needed is the part qualification as requested for any new serial components.

Table 1 presents a comparison between the main manufacturing processes for composite aerostructures (Autoclave, RTM, Vacuum infusion and SQRTM). This comparison is based on medium size parts (typically max 8 m x 1,5 m x 0,3 m), complex structures (integrating several ribs and/or spars) and relatively flat in the spanwise direction (if double curvature). Wing moveables (slats, flaps, ailerons, etc.) are parts that have these characteristics.

As shown in Table 1, SQRTM combines advantages from both prepreg and closed mold technologies.

From prepreg technologies:

- Use of qualified tough prepregs without additional costs for material allowables establishment.
- Existence of qualified automated lay-up processes (AFP or ATL) with the use of UD reinforcements; automation can be pushed further than autoclave (no vacuum bag, more repeatable process).
- A large variety of qualified prepregs from different suppliers.

From closed mold technologies:

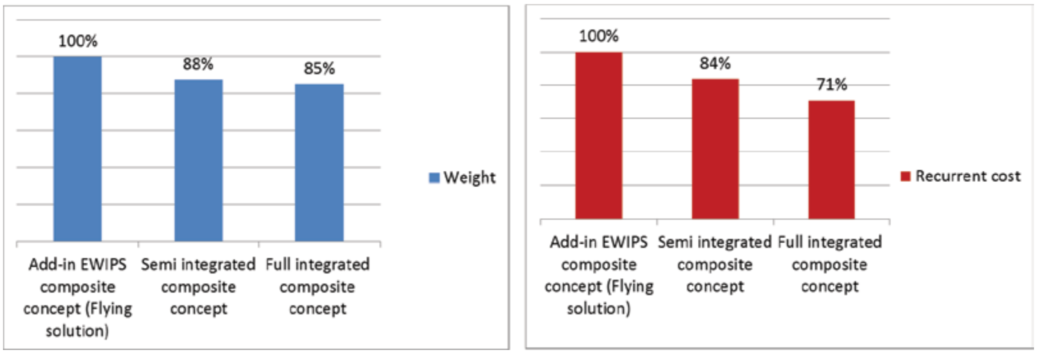
- High control on the thicknesses and the geometry (radii, plies conformity).
- High surface quality.
- Robustness, less scraps, less non conformities and repairs.
- Faster NDT inspection (due to the better surface quality) ; inspection time is estimated to be divided by about 15% compared to autoclave equivalent parts.
- Reduced direct and indirect costs related to inspection and non-conformities (by about 50%).
- High level of parts integration possible, allowing for curing costs reduction.
- Lower cost of ancillary materials and significantly lower energy consumption in comparison with autoclave.
- Reduction of assembly cost and lead-time (less shimming due to high dimensional tolerances, potential for more integrated parts, assembly automation easier due to close tolerances and geometry repeatability).
- Better buy-to-fly ratio as near net shape parts are produced (material attrition is reduced).

SQRTM is very suitable for wing components (slats, flaps, ailerons, etc.) with respect to the size, part complexity and aero quality requirements. For the typical business base of a commercial aircraft or business jet, the tools extra cost (closed mold) is balanced by the recurrent cost savings.

Table 1. Comparison between SQRTM, autoclave, RTM and vacuum infusion.

					Concerned criteria		
	Autoclave	RTM	Vacuum Infusion	SQRTM	Quality / Performance	Cost	High production rate
Curing time	-	+	-	+		√	√
Curing cost	-	+	++	+		√	
Material supplier single source	+	-	-	+		√	
Material costs	0	0	0	0		√	
Material properties	+	-	-	+	√	√	
Part/process qualification	0	0	0	0		√	
Lay-up automation	+	0	0	+		√	√
Buy to fly ratio	-	+	-	+		√	
Molding automation	-	+	-	+		√	√
Structure integration	-	+	-	+	√	√	√
Geometry robustness	-	+	-	+	√	√	√
Internal quality robustness	-	+	--	+	√	√	√
Tools cost	+	0	+	0		√	

Figure 2. Weight and cost analysis of composite slat design concepts.



MORE INTEGRATED COMPOSITE WING MOVEABLES

Since the 2000s, SONACA has successfully conducted a series of research and development programs to develop composite wing moveables. Based on the advantages presented in the previous section, SQRTM was selected. The development followed a building blocks approach to introduce new technologies (SQRTM, automation) step-by-step and increase gradually the level of integration with new design concepts. In addition to structural integration, SQRTM is also perfectly adapted to integrate functionalities such as protection for erosion, ice protection system, etc. The benefits of SQRTM combined with automation to produce more integrated components were demonstrated on two type of structures: slats and flaps. Following sections present these two cases.

Case #1: Slats

In 2005, we launched a vast R&T program to develop full composite slats combined with an electric wing ice protection system (EWIPS). Different design concepts were considered: the system can be embedded into a separate skin that is assembled with fasteners on the composite slat ("add-in EWIPS" concept) or it can be integrated into the structural skin of the composite slat; for the structure, two configurations were developed: a semi-integrated slat with a composite nose and trailing edge that are cured separately and then assembled, and a full integrated slat with a nose and trailing edge that are cocured. For the latter configuration, the back skin remains separated in order to allow for the assembly of the metallic ribs.

A weight and cost analysis of the different concepts has been performed. Compared to the "add-in EWIPS" slat concept (current flying concept), the weight of the integrated slat concepts is 10 to 15% lower and the recurrent cost is 15 to 30% lower, depending on the integrated slat concept (semi-integrated or fully integrated).

In order to assess and validate both integrated slat concepts, two slat demonstrators were designed and manufactured. The semi-integrated slat demonstrator is representative of the geometry of a short-to-medium range commercial aircraft slat (with a reduced span of 2,2 m) and the integrated slat demonstrator is representative of the geometry of a long range commercial aircraft slat (3,5 m).

The nose skin includes:

- A skin with a hybrid laminate composed of CFRP UD tape (AS4/8552 RC34 AW194), GFRP fabric (8552/42%/220/G), adhesive films (FM300M03), a heating mat and a metallic (Titanium) erosion shield. The erosion shield is integrated into the laminate during the curing of the skin.
- Cocured composite rib feet composed of CFRP fabric plies (AGP193/8552S RC40).

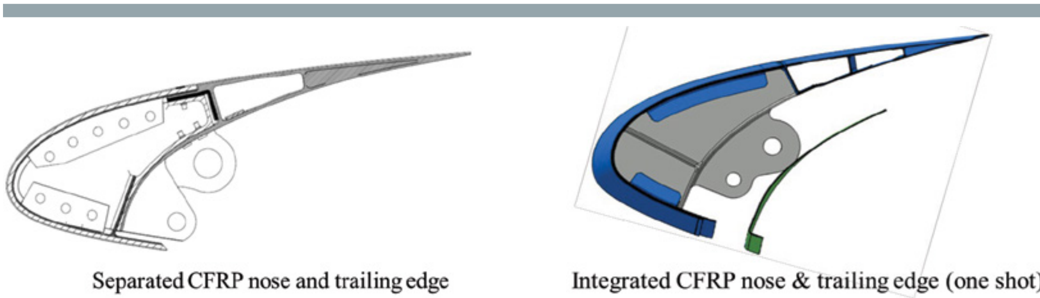


Figure 3. Design principle (left : semi-integrated slat; right: fully integrated slat).

Figure 4. Pull-off tests on rib foot - skin connection.

The metallic ribs are riveted to the cocured rib feet. The goal is to eliminate fasteners in the skin in order to increase aerodynamic and deicing performances. The composite stringer that makes the connection between the nose and the rear part of the slat can be either integrated to the nose or to the back skin. The stringer is composed of CFRP UD plies (AS4/8552 RC34 AW194).

An exhaustive stress analysis of the demonstrators using finite elements models was performed. The key point was the analysis of the cocured joint between the composite rib feet and the composite skin. Simulations included damages at the joint representative of a barely visible impact damage and largely visible impact damage. The damage size was defined with an impact test campaign (up to 140 J) on a representative nose skin. The allowable of the rib foot - skin connection was determined by pull-off tests on coupons representative of this connection.

For the manufacturing of the slats, SQRTM was selected due to the level of parts integration, the strict dimensional requirements for the aerodynamic performance and the capability to integrate the embedded heating mat and erosion shield.

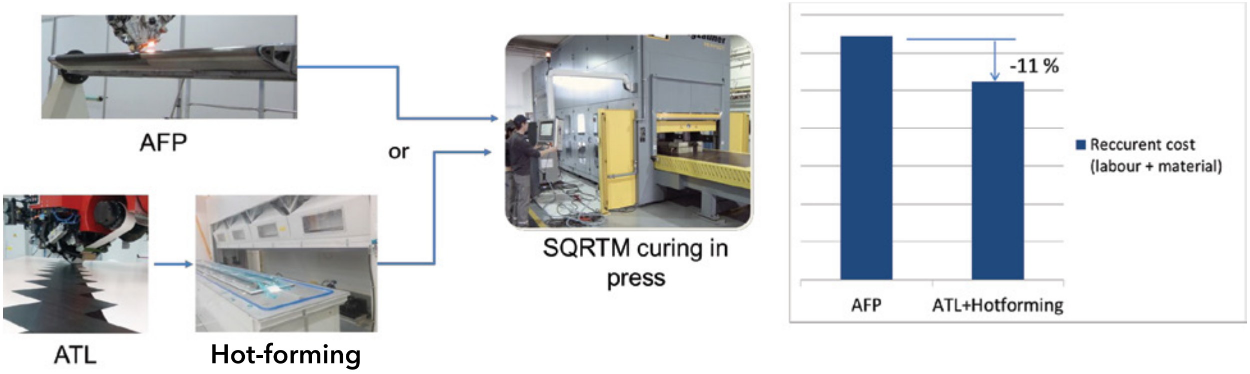
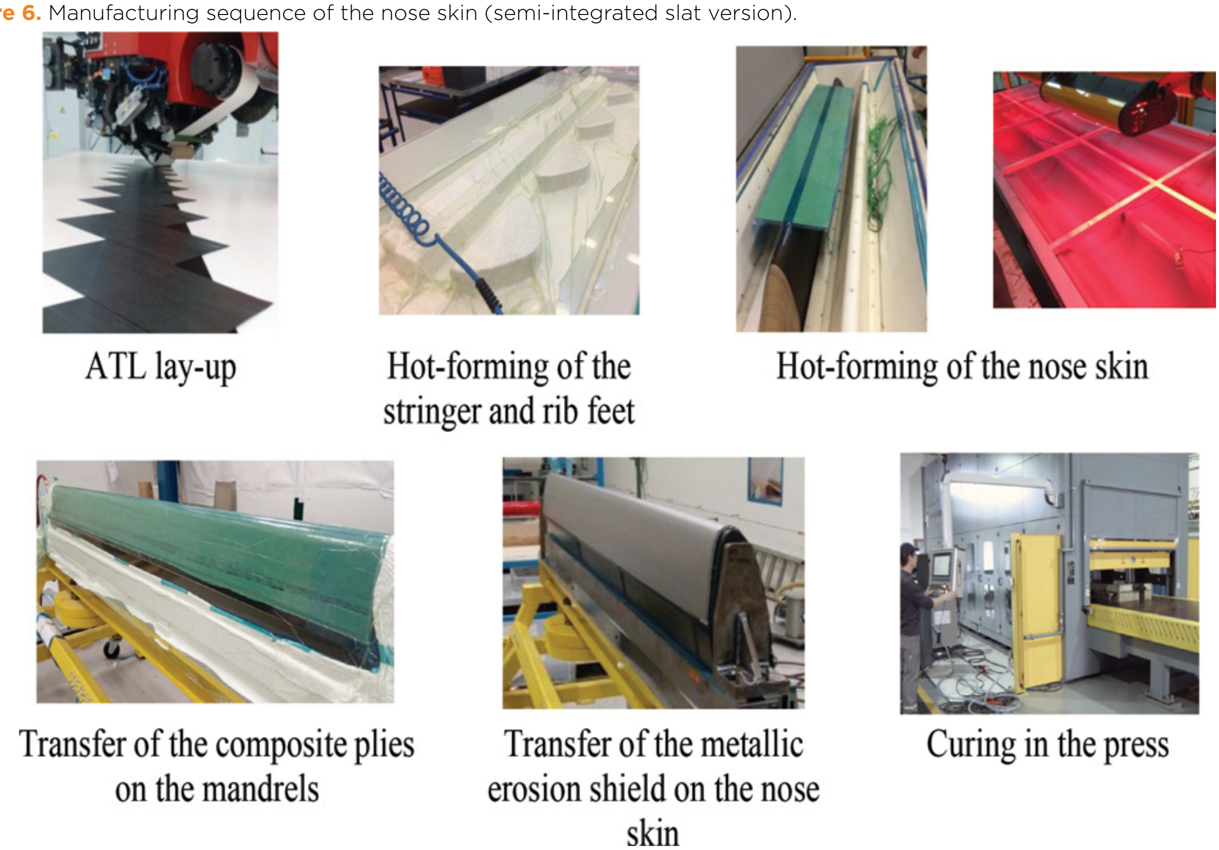


Figure 5. Cost trade-off on the lay-up process for a composite slat nose of a short-medium range commercial aircraft.

For the nose skin, automated in-shape lay-up (with an AFP machine) and automated high speed flat lay-up (with an ATL machine) combined with hot-forming were compared. For the considered slat geometry (small radius, no double curvature), the second option was better in terms of recurrent cost with much less process adjustment needed to get a preform without defects.

The SQRTM mold is composed of a series of mandrels in order to allow for the rib feet integration and part demolding. The manufacturing sequence of the nose (semi-integrated version) is illustrated in Figure 6. The CFRP plies of the nose skin were draped flat with a high speed ATL machine and then hot-formed with a membrane under vacuum. The stringer and rib feet were also hot-formed and then inserted between the mandrels of the SQRTM mold. The CFRP plies were transferred onto the SQRTM mandrels. The heating mat, GFRP plies and adhesive films are placed manually on top of the CFRP plies and finally the metallic erosion shield (cold stretched) is placed on the nose skin laminate. The mold is closed and placed in the press. The part is cured with injection of 8552 resin to apply pressure on the part.

Figure 6. Manufacturing sequence of the nose skin (semi-integrated slat version).



For the demonstrator with integrated trailing edge, since the top skin extends from the nose up to the tip of the trailing edge, the CFRP plies of the top skin were draped by ATL on a pre-shaped tool in order to facilitate the final hot-forming of the nose (Figure 7). Before transferring the top skin on the SQRTM mandrels, the rib feet, the spars (hot-formed) and the lower skin of the trailing edge are positioned in the mold between the mandrels.

In total, 4 nose skin demonstrators of the semi-integrated version (with cocured rib feet and stringer) and 1 demonstrator of the full integrated version (with cocured rib feet and trailing edge) were manufactured. Parts were inspected through a series of non-destructive and destructive tests. All parts showed a very high quality. The manual US inspection did not detect any defects and the micrography analysis performed on some coupons extracted from one of the part confirmed the high quality of the laminate (Figure 8): there are no delamination and no plies wrinkles; the noodle fillers of the stringer and rib feet are positioned correctly; the radii of the stringer and rib feet are compliant with the requirements.

Thickness measurements were performed: over the 206 control points, only 3 were slightly above the requirement. This shows the very good dimensional control obtained with SQRTM for such a complex part with a hybrid laminate (mixed of CFRP/GFRP plies, adhesive films and metallic sheet).

After inspection, parts were assembled and painted. For the semi-integrated slat version, a RTM composite trailing edge was taken from the serial production in order to perform the assembly. For the full integrated slat version, the back skin was manufactured with 8552/AS4 prepreg (ATL lay-up, hot-forming of the stringer area and curing in autoclave due to the simplicity of the part). The metallic ribs and composite skin were located with respect to jig references; due to the good control of the location of the cocured rib feet, there was no mismatch with the metallic ribs positions.

In order to validate the concept of the cocured rib feet and to better estimate the sizing margin of the rib feet-skin connection, a static test on one of the semi-integrated slat demonstrator has been performed. The test component length was reduced to 1,5 m, centered on the master rib. The test conditions were representative of the most critical load case. Two impacts were inflicted to the top skin at the cocured rib feet location: a BVID impact (35J) was applied before starting the test and a VID impact (90J) was done at the same location as the BVID impact during the test sequence. After each impact, the structure was loaded successively up to limit and ultimate loads with no failure or damage propagation (impact damage was controlled after each loading with US inspection). Finally, the structure was loaded up to 1,72 * UL * EKDF. First damage occurred at 1,3 * UL * EKDF but the structure has continued to withstand the increasing load up to the last step. The test had to be stopped due to the limitation of some parts of the test jig. Ultrasonic inspection performed after test shows

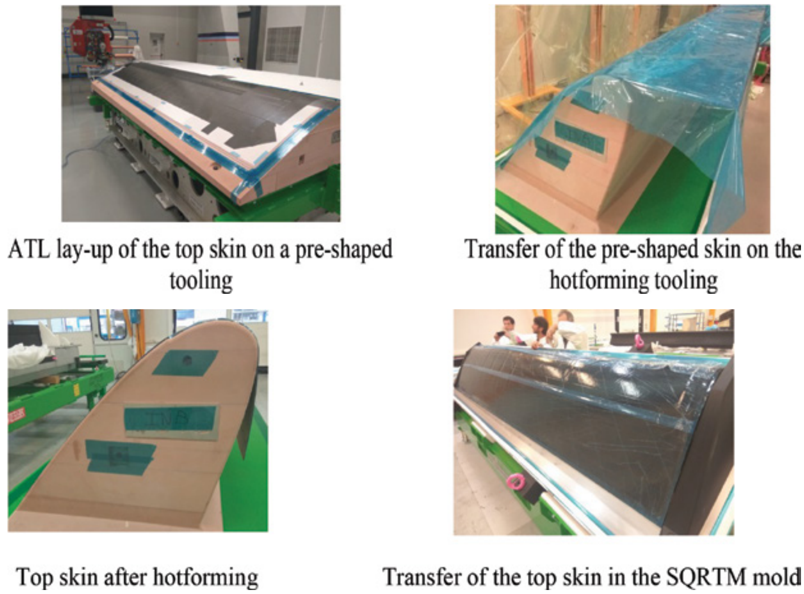


Figure 7. Molding steps of the slat with integrated trailing edge.

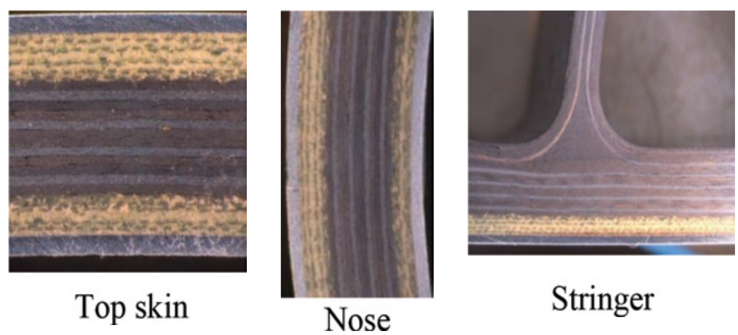


Figure 8. Micrography analyses on in-situ coupons.

Figure 9. Full integrated slat.

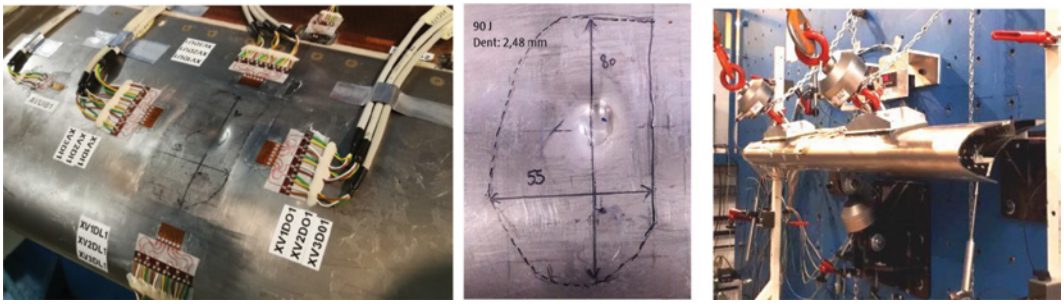


Figure 10. Static test on a slat subcomponent (1,5.

a large delamination between the skin and top rib foot. This rib foot is almost fully disconnected. This static test has proved the viability of the cocured rib feet concept.

Case #2: Flaps

2008 saw the launch and the development of composite rear moveables. The first flap structures were manufactured with hand lay-up of woven prepreg cured in autoclave. From 2010, SQRTM was developed, combined first with hand lay-up[5] then with Automated Tape Lay-up[6]. Eventually, based on SQRTM capabilities, more integrated flap concepts were developed and tested. To support the trade-off between integrated concepts, a weight and cost analysis was performed. The following concepts were considered.

Integrated designs allow for a weight reduction of 3-5% with respect to the black metal concept. The integrated concept with the spars, nose and trailing edge cocured to the lower skin could offer additional weight saving with a continuous preform between the skin and the nose but that would add some complexity and cost on the preform. The integration of the spars, nose and trailing edge to the lower skin combined with ATL lay-up and

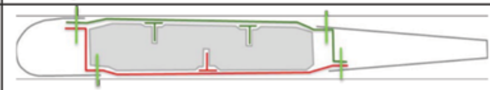
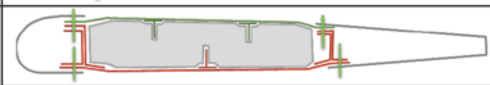
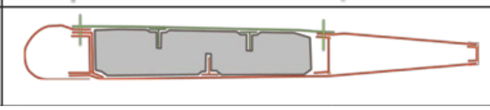
Concept		Material and process	Features
"Black metal"		CFRP fabric Hand lay-up /Autoclave	6 CFRP parts (metallic ribs) 4 spanwise lines of fasteners
1 spar integration		CFRP fabric Hand lay-up /Autoclave	4 CFRP parts (metallic ribs) 4 spanwise lines of fasteners
2 spars integration		CFRP UD tape ATL/SQRTM	4 CFRP parts (metallic ribs) 4 spanwise lines of fasteners
2 spars & ribs integration		CFRP UD tape ATL/SQRTM	4 CFRP parts (with cocured intermediate composite ribs) 4 spanwise lines of fasteners
2 spars, nose & trailing edge integration		CFRP UD tape ATL/SQRTM	2 CFRP parts (metallic ribs) 2 spanwise lines of fasteners

Table 2. Integrated flap concepts.

SQRTM offers a significant cost reduction compared to the black metal solution with hand lay-up and autoclave (-20%). Indeed, this level of integration enables to save time and cost on the manufacturing of the primary parts (less curing cycle) and on the final assembly (less fasteners).

In order to mitigate risks, we have followed a building blocks approach. After the manufacturing of a series of flap components in SQRTM with manual lay-up of prepreg fabric, SONACA developed design concepts using UD tape materials to combine the high speed of automated lay-up and the integration capability of SQRTM. The first step towards more integrated flap was the manufacturing of 3 demonstrators (1,2 m) with the cocuring of both spars to the lower skin.

The CFRP material used was UD tape 8552/AS4. Each spar was composed of a C and Z preforms. The preforms of the spars and the blade stiffeners were draped flat with ATL and then hot-formed under vacuum. The skin was also draped with ATL. The preforms were then inserted into the SQRTM mould and cured in a press with the injection of 8552 resin to apply pressure on the part. After demolding, the inspection of the part (visual, US, dimensional and micrography) showed the high quality of the part. All thickness measurements (32 control points) were within the tolerance (-8%/+10%). The internal quality was very good as shown on the US C-scan and micrography.

A manufacturing trial was performed to integrate a rib in addition to the spars. If the SQRTM process showed the capability to perform such an integration, this integration route was not pushed further based on the cost analysis which reveals that integrating the ribs does not offer any significant cost savings.

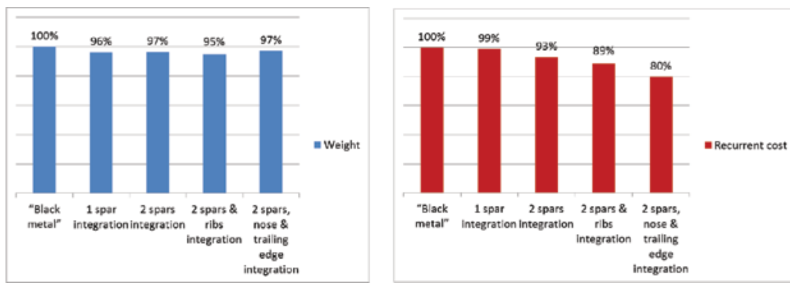


Figure 11. Weight and cost analysis of the integrated flap concepts.

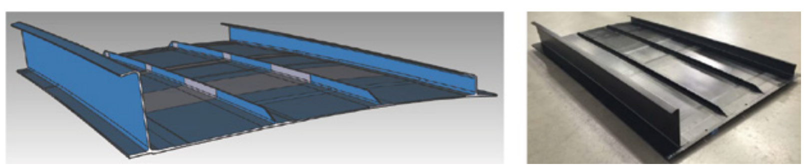
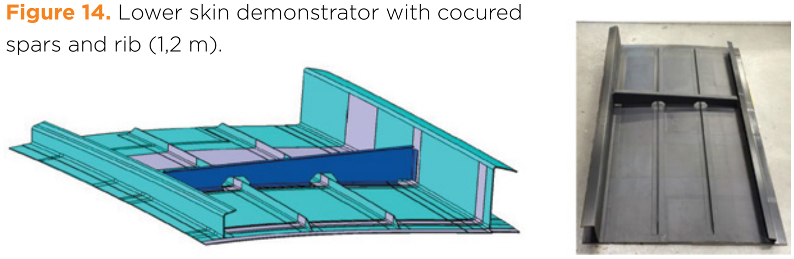


Figure 12. Lower skin demonstrator with cocured spars (1,2 m).

Figure 13. C-scan and micrography from the lower skin demonstrator with cocured spars.

Figure 14. Lower skin demonstrator with cocured spars and rib (1,2 m).



The design of the flap with the spars, nose and trailing edge integrated into the lower skin was based on the geometry of a serial part production. It was representative of the outboard flap of a business jet (4,3 m). The general thicknesses were derived from the existing design but some design adaptations were performed to allow for the integration of the spars, nose and trailing edge. Mainly, the plies drop-off in the nose and trailing edge were adapted to allow for the demolding of the mandrels after curing. The CFRP material used was UD tape 8552/AS4.

All preforms were draped by ATL, hot-formed and then inserted in the SQRTM mould. The mandrels inside the nose and trailing edge are metallic and single parts. The demolding had been checked by analysis on the 3D models. The manufacturing sequence is illustrated in the Figure 16.

After demolding, the lower skin was controlled by visual and ultrasonic inspections, thickness measurements and micrography analysis. The overall quality was good; a few local defects (porosities) were detected by ultrasonic inspection. These were due to insufficient compaction, mainly due to misplacement of some local CFRP patches at rib stations. These CFRP patches were placed manually. The thickness measurements also exhibited a few control points out-of- the tolerance (over-thickness), which shall be related to previous compaction issues. These issues were not related to the SQRTM process. A second demonstrator will be manufactured with few process adjustments. Some micrography analyses were performed on coupons extracted in the overlength of the part. The internal quality was good. There were no plies wrinkles and the noodle fillers were positioned correctly.

The concept of the spars cocured to the lower skin has been validated through a series of tests: low energy impacts, pull-off tests and a bird impact test. For that purpose, two components (1,2 m) with spars cocured to the lower skin were assembled with metallic ribs and composite upper cover and nose.

Figure 15. Design of the full scale flap lower skin with cocured spars, nose and trailing edge.

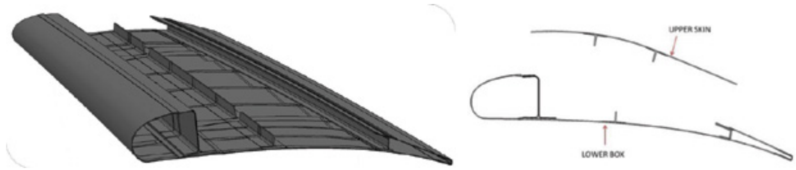
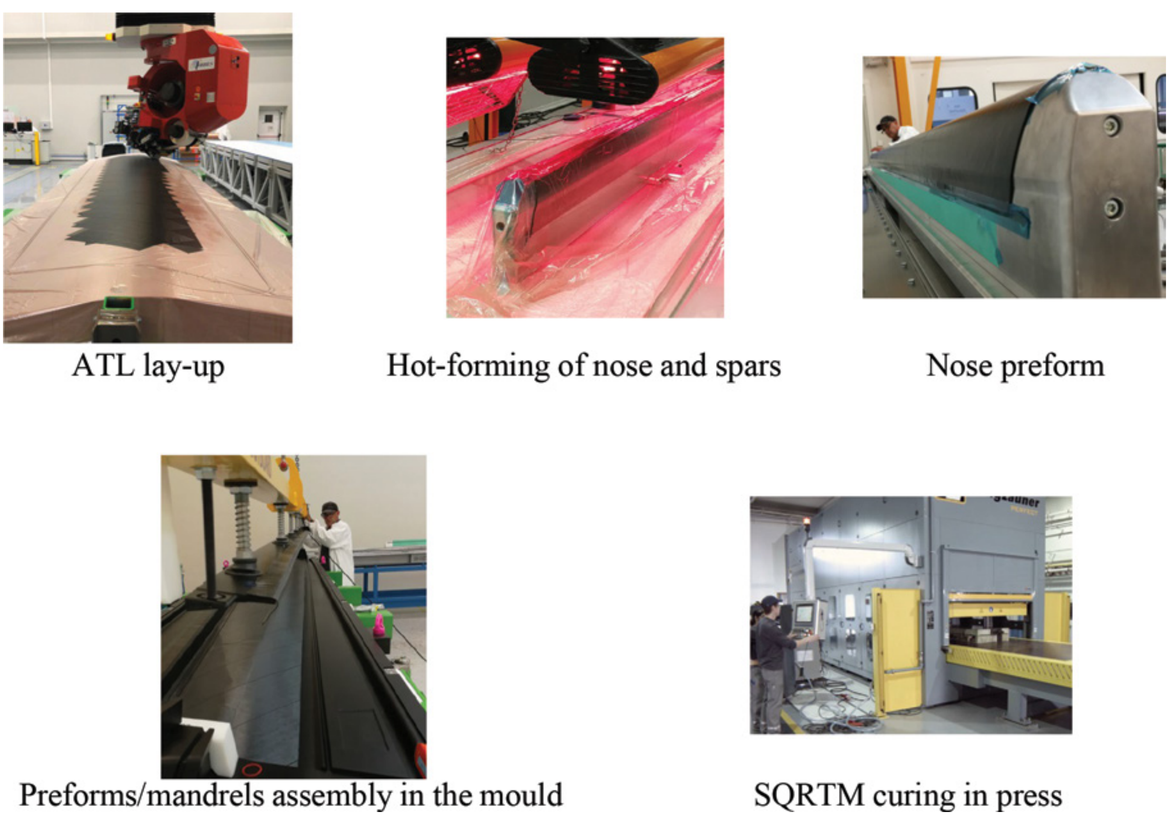


Figure 16. Manufacturing of the flap lower skin with cocured spars, nose and trailing edge.



A series of impacts up to 140 J were performed at different locations of the flap lower skin, in particular at the location of the cocured spar-skin connection. The impact sensitivity of the lower skin with cocured spars was not found higher than that of a standard riveted concept particularly when impacting on top of spars and stringers or on plane skin area (Figure 20).

Some pull-off tests have been performed on the spar-skin connection. Results from these tests were compared to the allowables that had been determined for T-junction in RTM multi-cells box in past projects. The pull-off strength of the cocured spars is much higher for equivalent thicknesses.

The aim of the bird impact test was to evaluate the bird impact resistance of the flap concept under the most critical impact condition and configuration. The structure was hit by a 1,8 kg bird at 108 m/s in a full extended flap setting. The numerical model successfully predicted the perforation of the nose skin, front spar and lower skin that were observed during the test. The cracks occurred in the skin and spar laminates and not at the cocured spar/skin interface.

CONCLUSIONS

The development of SQRTM at SONACA has been very successful all the way. After a very short time development, the company first qualified SQRTM in 2015 for the serial production of the flaps of a regional jet. Since then, the process has continuously pushed forward the technology by first combining it with high speed automated lay-up and then increasing parts integration. The manufacturing and test of a series of full scale composite wing moveables (slats and flaps) have demonstrated the benefits of SQRTM to produce complex parts, medium size (typically 8 m x 1,5 m), with a high level of integration. Each demonstrator presented a very high quality with no or minor process adjustment needed. With the combination of automation and integration, SQRTM allows for significant recurrent cost reduction: 20% for the integrated flap with respect to a "black metal" design using hand lay-up and autoclave; 30% for the integrated slat with respect to the current flying composite concept. For some wing moveables like ailerons which can be fully integrated as a one-shot multi-cells box, the cost reduction is expected to be even higher (typically 38 assembled parts are replaced by a single composite box cured by SQRTM). An aileron produced by ATL and SQRTM is currently under development and demonstrators will be manufactured and tested. Lots of components could benefit from SQRTM: wing components (such as slats, flaps, ailerons, spoilers, winglets), fuselage parts (such as floor beams, doors) and engine parts (such as outer shrouds of low pressure compressor, fan blades).

Figure 17. Flap lower skin demonstrator with cocured spars, nose and trailing edge (4,3 m).

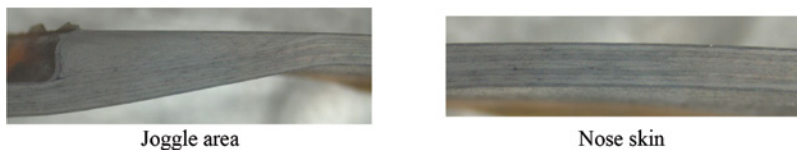


Figure 18. Micrography analyses on coupons extracted from the full scale integrated lower skin.

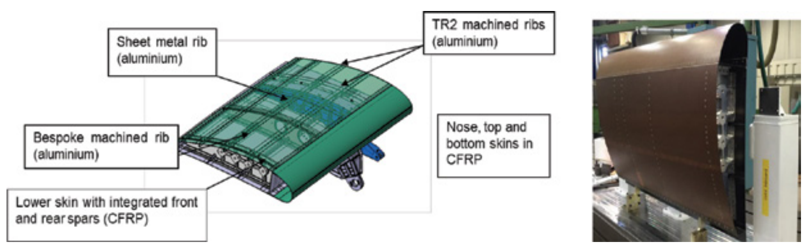


Figure 19. Cocured spars flap demonstrator.

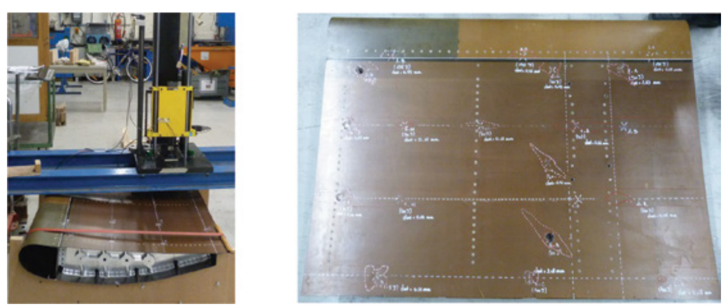


Figure 20. Low energy impacts (BVID/VID) on cocured spars flap concept.

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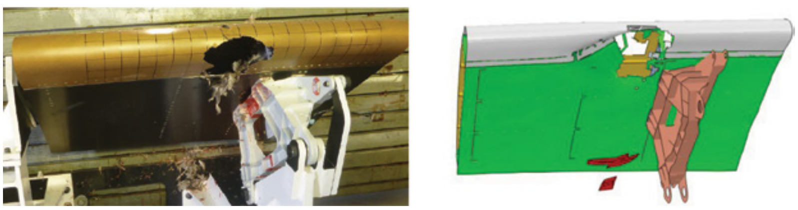
Figure 21. Pull-off test on cocured spar-skin junction.

Figure 22. Bird impact test on the cocured spars flap concept.



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