OUT OF AUTOCLAVE PROCESSING FOR ELECTRIC AVIATION USING SAME QUALIFIED RESIN TRANSFER MOLDING

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ABSTRACT

Increased composites use in the aerospace industry has led to lighter weight and lower maintenance aircraft. Additional reduction in weight remains a goal, especially for the growing Electric Aviation market where battery energy density is limited. Applications for passenger or cargo missions include Regional Air Mobility, General Aviation, eSTOL and eVTOL. Further goals include improved laminate quality, reduced manufacturing costs and cycle times, as well as expedient FAA and other regulatory certification.

Same Qualified Resin Transfer Molding (SQRTM) is a unique out of autoclave (OOA) manufacturing process with a relatively clear path to certification since SQRTM uses prepreg material in a closed-mold to produce a net-shape composite structure. Demonstrating equivalency to existing databases such as NCAMP can ease the path to certification, compared to other OOA processes, since SQRTM has been certified for commercial aerospace structures by Boeing, Embraer, and other airframe manufactures.

In the SQRTM process, prepreg is laid up and compacted per established best practices. The preform is assembled into an SQRTM matched-metal tool. The tool is heated, resin pressure in the preform is increased to 5.5-7 bar (80-100psi), and the tool continues to the cure temperature.

This paper will address how SQRTM can offer opportunities for the Electric Aviation market. Design opportunities will be presented along with potential improvements in laminate quality provided by SQRTM. Approaches to reduce manufacturing cycle times and recurring costs will be included, as well as examples of current SQRTM aircraft structures that are certified for commercial and military use.

Keywords: Electric Aviation, SQRTM, Out of Autoclave, OOA, Certification, Automation
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1. INTRODUCTION

Composite materials are somewhat unique in that, unlike metals, the composite material is made when the part is made. The quality of a composite part depends on controlling the appropriate processing parameters. A poorly controlled manufacturing process will result in a composite with poor quality. A laminate with 2% void content results in a drop of approximately 20% in inter laminar shear strength and flexural strength and approximately a 10% reduction in flexural modulus [1]. Void content in composite materials is controlled by vacuum and resin hydrostatic (fluid) pressure [2]. The process parameters that must be controlled during a composite manufacturing process are time, temperature, vacuum, ply thickness, fiber bed pressure (compaction) and resin hydrostatic pressure. Time, temperature, and vacuum are controlled reasonably well in an autoclave manufacturing process. Autoclaves and OOA vacuum bag/oven manufacturing processes do not control ply thickness, fiber bed pressure (compaction) and resin hydrostatic pressure directly; they result from time, temperature, and resin flow [3].

The SQRTM manufacturing process controls ply thickness and fiber bed pressure directly via the closed, match-metal tooling. The resin hydrostatic pressure is controlled directly via an injection system set to specific pressure. This allows the SQRTM process to consistently produce composite structures with excellent laminate quality.

The SQRTM manufacturing process uses toughened prepreg materials to produce net-shape composite structures via a closed-mold OOA process. SQRTM has been used with many well-known and previously certified aerospace prepregs including: Toray 3900, Hexcel 8552 and Solvay 5250-4. The SQRTM process will generally closely follow the process specification used for prepreg characterization and development of an allowables data base. Additional new prepreg materials being characterized by NCAMP are being used for SQRTM development programs.

A brief outline of the SQRTM process is given below.

Prepreg can be laid up on the SQRTM tooling using traditional lay-up and compaction techniques. Many opportunities exist to incorporate automation in the SQRTM manufacturing process. Existing automated prepreg lay-up technology such as automated tape lay-up (ATL) and fiber placement (FP) is also used for SQRTM preform lay-up [4].

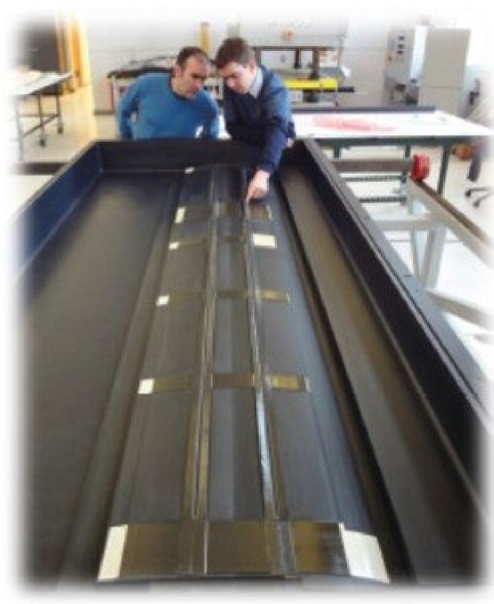

Figure 1 Tool & Preform Assembly

The tooling and preforms are assembled. The tooling has been designed to create the final part thickness and geometry at the cure temperature. All tooling pieces are precisely located at full tool closure.

The tool is prepared for the injection and cure cycle. Injection port blocks and the associated single inlet and single outlet plumbing are mounted to the tool. Tool thermocouples and an outlet pressure transducer are installed and connected. The sensors are checked for correct readings.

The tool is shuttled into a SQRTM workcell, which consists of a clamping and heating press and a heated and flow-controlled injection system. The press applies clamping pressure to the tool. Once the tool is closed and clamped to approximately 10 bar (~150 psi) it is heated to the injection temperature. Heating ramp rate is typically 2.8 C°/min (5° F/min).

Injection resin is loaded into the SQRTM injection system. The resin injected is typically the same as the prepreg resin. Untoughened versions of the prepreg resin are commonly used to provide reduced viscosity and improved handling. This resin is heated by the injection system to the injection temperature.

Once the tool has reached the injection temperature the resin is injected into the tool to create hydrostatic pressure within the tool and preform.

Note: The injection resin does not infuse the prepreg, it is only used to pressurize the resin in the prepreg and act as an edge dam to prevent excess prepreg resin bleed during heatup and cure (as can be seen in Figure 3 and discussion, further below). Maintenance of laminate hydrostatic pressure is well-known to prevent void formation.

Figure 2 shows one half of a typical SQRTM tool and the resin flow path along the perimeter of the tool and to the edges of the composite part.

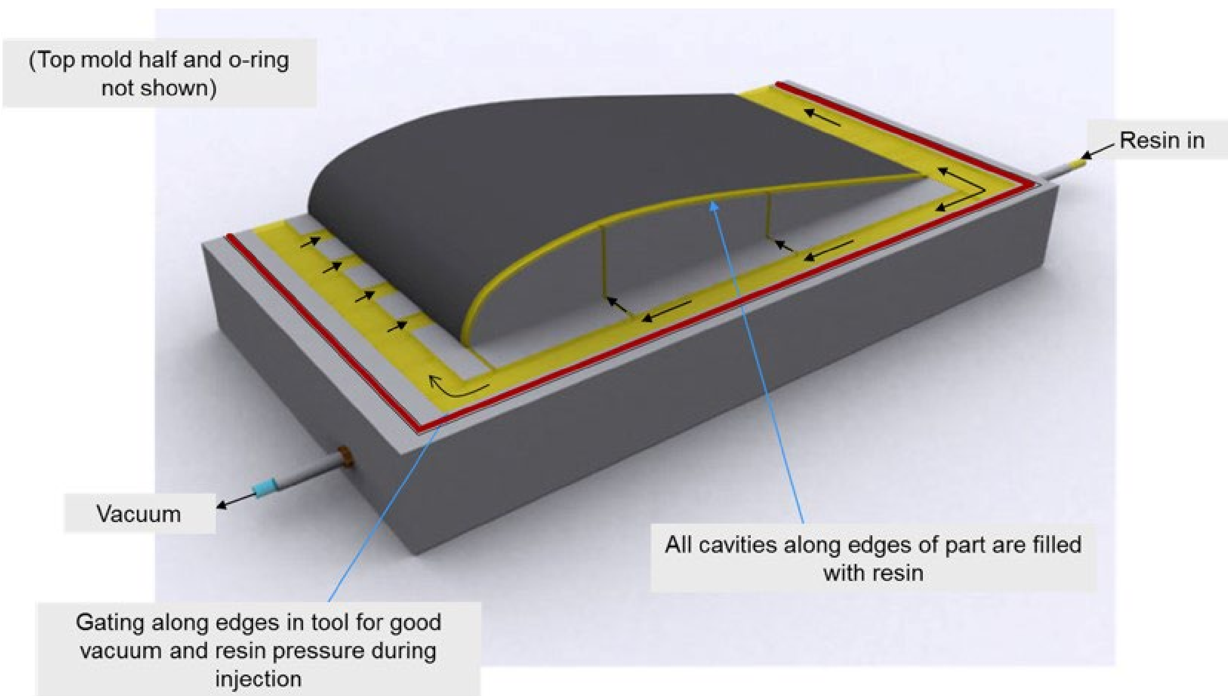

Figure 2 Resin Flow within SQRTM Tool

Once the injection is complete and an internal hydrostatic pressure is developed within the tool - typically 7 bar/100 psi - the tool temperature is increased to the cure temperature. This temperature is maintained for the duration of the cure cycle per the standard aerospace process specification used to develop the material allowables.

Upon completion of the cure cycle the tool is cooled via the SQRTM workcell or stand-alone cooling station. A controlled cooling cycle, typically 2.8 C°/min (5° F/min) is usually conducted. The cooling rate can be accelerated if allowed by the process specification.

Composite structure is demolded from the tool using tool handling fixtures.

The SQRTM tooling is cleaned and prepared for another cure cycle like other composite cure tooling.

1.1 SQRTM Bridge to Existing Material Database

The SQRTM process provides a path from autoclave manufacturing to an OOA manufacturing process with no need to qualify new materials. If existing qualified material data exist, such as those provided through NCAMP or through airframe or supplier-owned databases, the equivalency of the SQRTM laminates can be demonstrated to use the existing database as follows.

An initial testing phase of test coupons cut from "bridge panels" made with SQRTM is conducted to show equivalency of SQRTM laminates to the existing material database. A typical number of panels to support such tests is approximately 30-35 panels of 450mm x 450mm (18" x 18"). This approach has been used for FAA certified commercial aircraft structures such as Boeing 787, as well as military applications such as Northrop-Grumman Global Hawk. A sample test matrix for this phase is included in Table 1 below. Radius Engineering has a library of flat panel tooling that can produce the required test coupons.

Table 1 Sample Equivalency Test Matrix

Lamina Equivalence Testing								
Test Type	Lamina/Laminate Type	Test Method	Strength	Modulus	Priority	Quantity and Test Condition		Notes
						RTD	ETW (Optional)	
0° In-Plane Tension	Lamina	ASTM D3039	X	X	1	14	14	[1] [3]
0° In-Plane Compression	Lamina	ASTM D6641	X	X	1	14	14	[1] [3]
90° In-Plane Tension	Lamina	ASTM D3039	X	X	2	14	14	[1] [3]
90° In-Plane Compression	Lamina	ASTM D6641	X	X	2	14	14	[1] [3]
±45° In-Plane Shear	Lamina	ASTM D3518	X	X	1	14	14	[1] [3]
Short Beam Shear	Lamina	ASTM D2344	X	-----	1	14	14	[1] [3]
0° Flexure	Lamina	ASTM D7264	X	X	2	14	14	[1] [3]
Open Hole Tension	25/50/25 Quasi	ASTM D5766	X	X	3	14	14	[1] [3]
Open Hole Compression	25/50/25 Quasi	ASTM D6484	X	X	3	14	14	[1] [3]
Compression After Impact	25/50/25 Quasi	ASTM D7136/D6641	X	-----	3	14	14	[1] [3]
Fiber Volume & Void Content	All Coupon Panels	ASTM D3171	-----	-----	1	All Panels	-----	-----

1.2 SQRTM Offers Reduced Recurring Cost

The SQRTM workcell with heated platens controlling the temperature ramp of metal tooling allows more efficient heat transfer than an autoclave. Autoclaves usually have a mixed load of tooling of various sizes and shapes. Such tools are heated by air or nitrogen gas circulating inside the autoclave. Heat transfer under such conditions is more variable than metal tooling in a workcell with platens where direct conductivity will occur from platens to tooling. Thus the SQRTM process allows more precise and faster temperature ramp rates while remaining within allowable limits per the original process specification. Faster cycle times will reduce recurring cost of manufacturing. Figure 3 shows a comparison of an SQRTM cure cycle and an autoclave cure cycle showing a time saving of 120minutes.

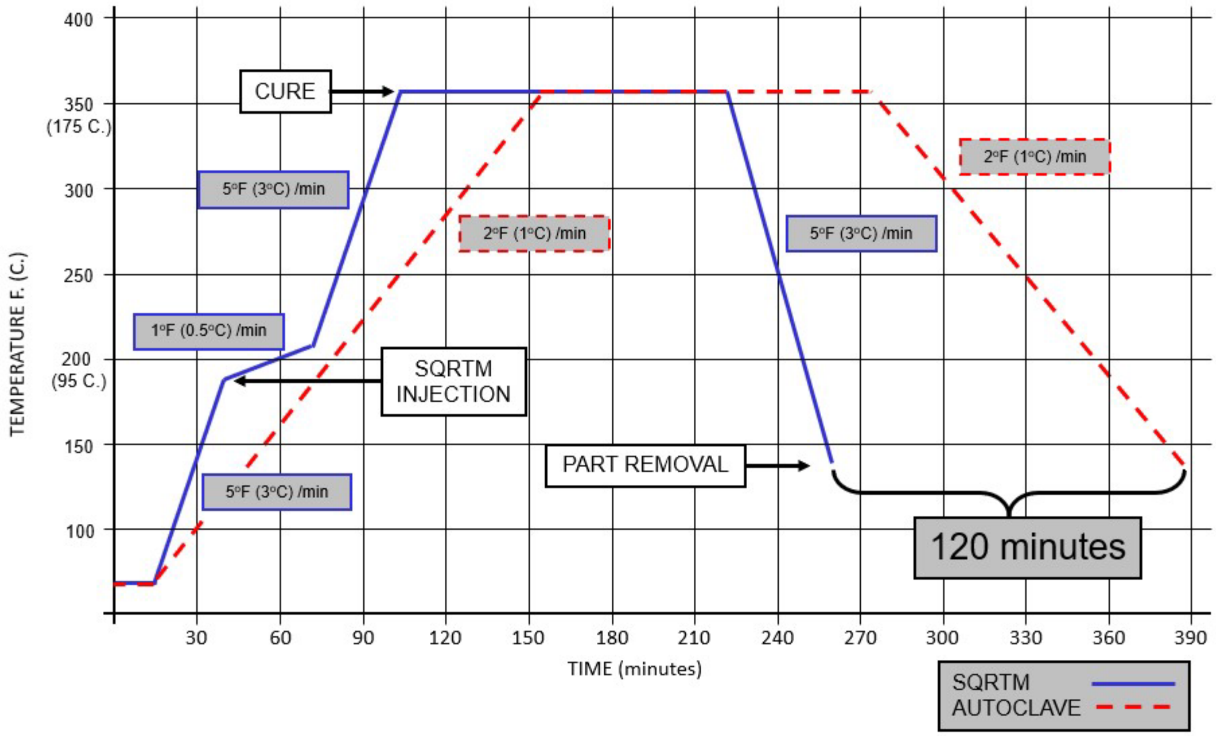

Figure 3 SQRTM vs. Autoclave Cure Cycle Thermal Profile

2. DESIGN EVALUATION

2.1 SQRTM Allows Unique Design Opportunities

The closed-mold nature of the SQRTM process allows greater dimensional control of composite structures because the tooling is closed to precise thickness at every location and every surface of the part, resulting in precise per-ply thickness. This provides opportunity for new design approaches for *part integration* and *determinant assembly* that are discussed in Section 2.2 and 2.3, respectively. A large tier 1 aerospace supplier has presented an extensive study on the methodology, approach, comparison, and test results of SQRTM and autoclave laminates and design demonstration applications. [5]

The closed-mold nature of the SQRTM process allows designing to higher fiber volumes which can result in lower weight structures. Typical autoclave specifications have upper fiber volume (Vf) limits typically around 59%. Controlling the range of laminate Vf to upper limits of the material specification can result in up to 2% weight savings. Higher fiber volumes (62%+) are also easily achievable with the SQRTM process creating the potential for additional weight savings**.**

SQRTM tools are designed to a specific fiber volume and part forming tool cavity vs. preform fill ratio. This provides a manufacturing process and tool that can ensures the part quality will not be influenced by variation in prepreg fiber and resin content. Figure 3 shows a photo of a test laminate and tool (mottled dark color) with an injected resin (pink color) in contrast to the prepreg resin (beige color). The test was made during process development to verify the injected resin does not go into the laminate. Radius Engineering conducted this test and produced the photo in Figure 3. The prepreg resin bleed occurs since the volumetric thermal expansion of the prepreg resin during tool heat up is greater than the tool thermal expansion, even when using aluminum tooling**.** As can be seen, the injected resin (pink color) does not enter the laminate, serving only to create an dege dam and produce hydrostatic pressure in the laminate.

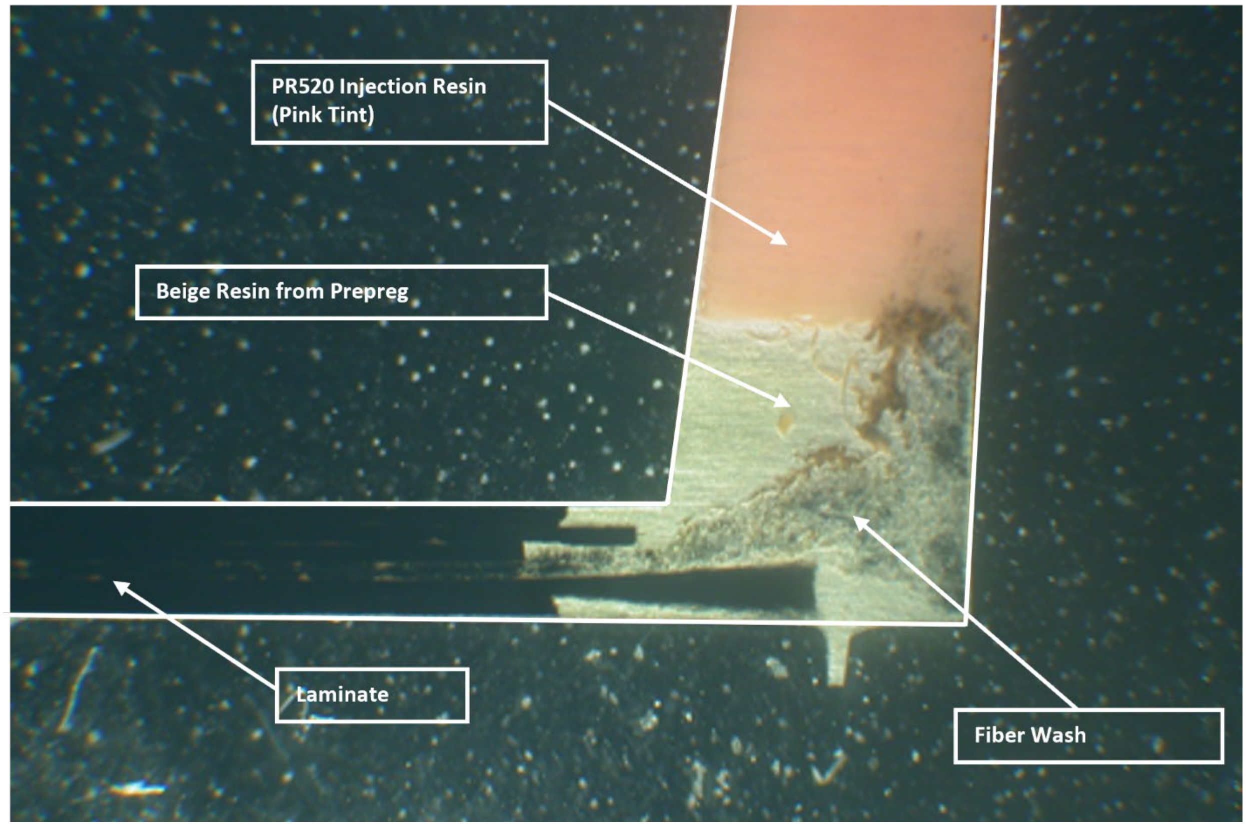

Figure 4 Prepreg Resin Bleed & Injection Resin Boundary

2.2 SQRTM Unitized Structures

With the control provided by the SQRTM tooling, unitized designs can be readily designed and produced. These configurations can eliminate bonding and fasteners, optimize the composite design, and reduce recurring labor via reduction in assembly labor. The need for "liquid shimming" is eliminated compared to autoclave or oven-cured parts. Figure 4 below shows many individual detail parts manufactured via an autoclave that are assembled vs. a single, co-cured, unitized SQRTM structure.

The degree of unitization or integration of features can vary for a variety of reasons. Depending on the configuration of the structure the degree of integration may be limited to simplify inspection operations or to allow assembly of components or systems. The SQRTM process permits more opportunities to optimize the part configuration compared to other OOA manufacturing processes. Figure 5 show a highly integrated UH-60 helicopter roof manufactured via SQRTM.

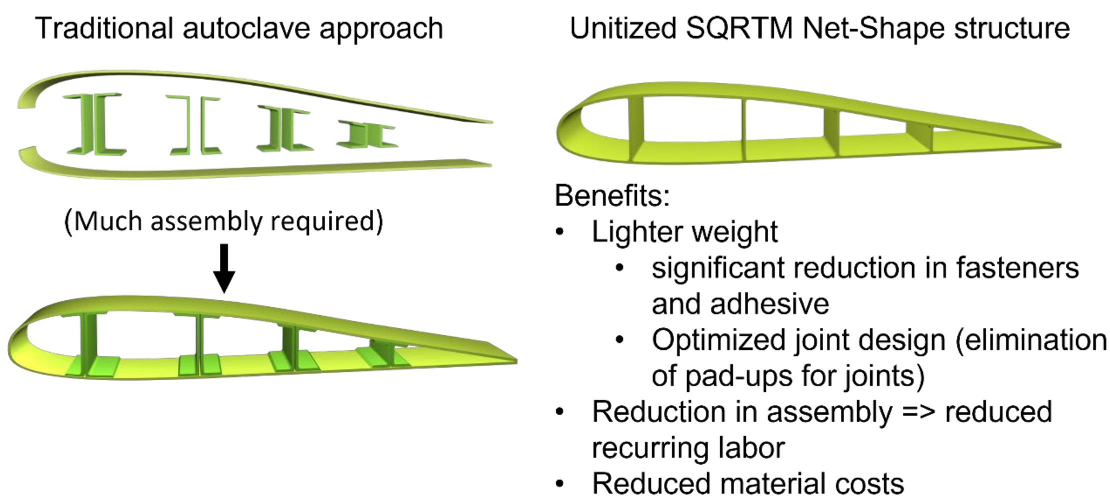

Figure 5 Non-Unitized vs. Unitized Design

Figure 6 Highly Unitized or Integrated Helicopter Roof

2.3 SQRTM Determinant Assembly Features

Determinant assembly features can be designed into a part or sub-structure to allow accurate and repeatable location during final assembly. For example, these features can locate a trailing edge laminate to the leading-edge section of a blade (see Figure 6 below). There are many other examples such as molded-in alignment features and bond line thickness control ridges (see Figure 7 below). With the dimensional control provided by SQRTM tooling these features can be relied on to accurately and repeatably provide positional control for a variety of design approaches**.**

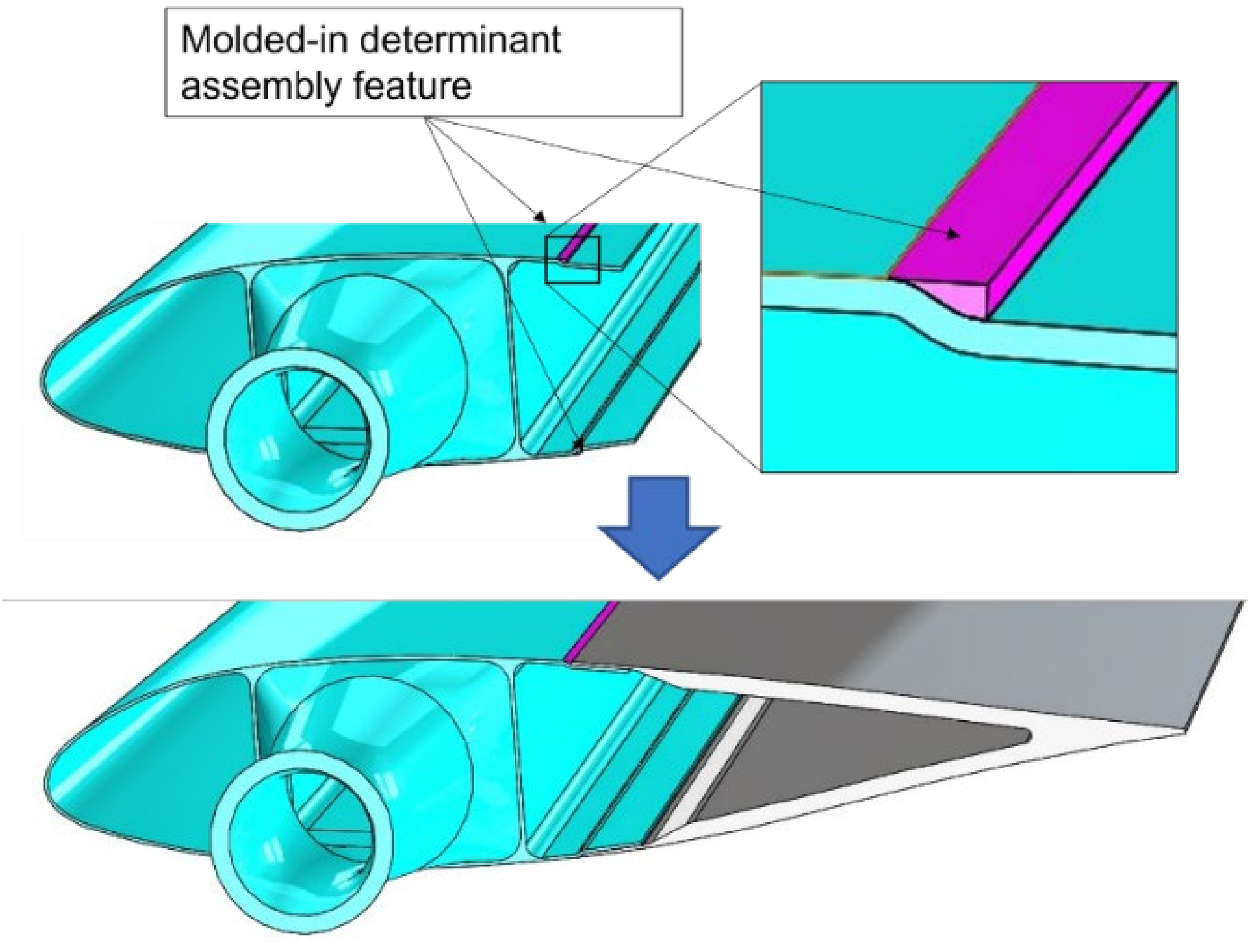

Figure 7 TE Locating Determinant Assembly Feature Example

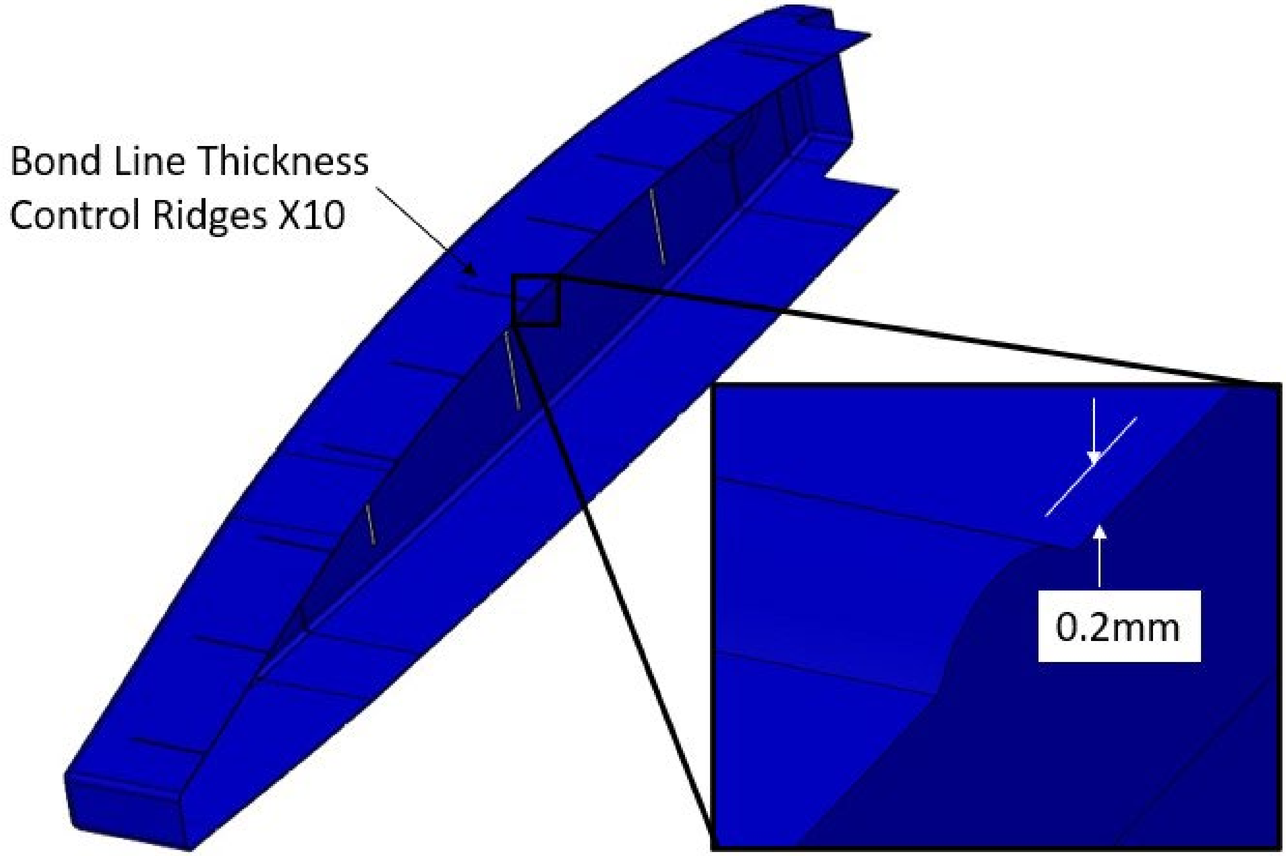

Figure 8 Bond Line Thickness Control Determinant Assembly Feature

2.4 Examples of SQRTM Manufactured Aircraft Structures

Several SQRTM manufactured aircraft structures have been successfully fabricated as demonstration articles. Table 2 lists some SQRTM manufactured commercial aircraft structures and their certification status.

OEM	Aircraft	Structure	Net-Shape Process	Certification Status	Manufacturer	Radius /Coexpair Content
Airbus	**A320**	**Outboard Flap**	RTM and SQRTM	Demonstrated and tested, not flying	Airbus	Composites Technology + Mfg. Equipment
Airbus	**A320**	**Nose Landing Gear Door**	SQRTM	Awaiting Flight Test	Coexpair	Composites Technology + Mfg. Equipment
Boeing	**B787**	**Leading Edge Slats**	SQRTM	Certified and Flying	Spirit AeroSystems	Composites Technology + Mfg. Equipment
Embraer	**E175-E2**	**Inboard Flaps**	SQRTM	Certification Underway	Sonaca	Composites Technology + Mfg. Equipment
Embraer	**E190-E2**	**Inboard and Outboard Flaps**	SQRTM	Certified and Flying	Sonaca	Composites Technology + Mfg. Equipment
Embraer	**E195-E2**	**Inboard and Outboard Flaps**	SQRTM	Certified and Flying	Sonaca	Composites Technology + Mfg. Equipment

Table 2 SQRTM Commercial Aircraft Examples

A number of military applications exist. One which has been reported on in Composites World [6] is a SQRTM multi-spar wing tip extension **is** flying on the Global Hawk RQ-4B. The main wing is an autoclave fabricated structure. The wing tip extension uses the original legacy main wing material system in an OOA SQRTM process. Figure 8 shows the Global Hawk with an inset CAD image of the wing tip extension.

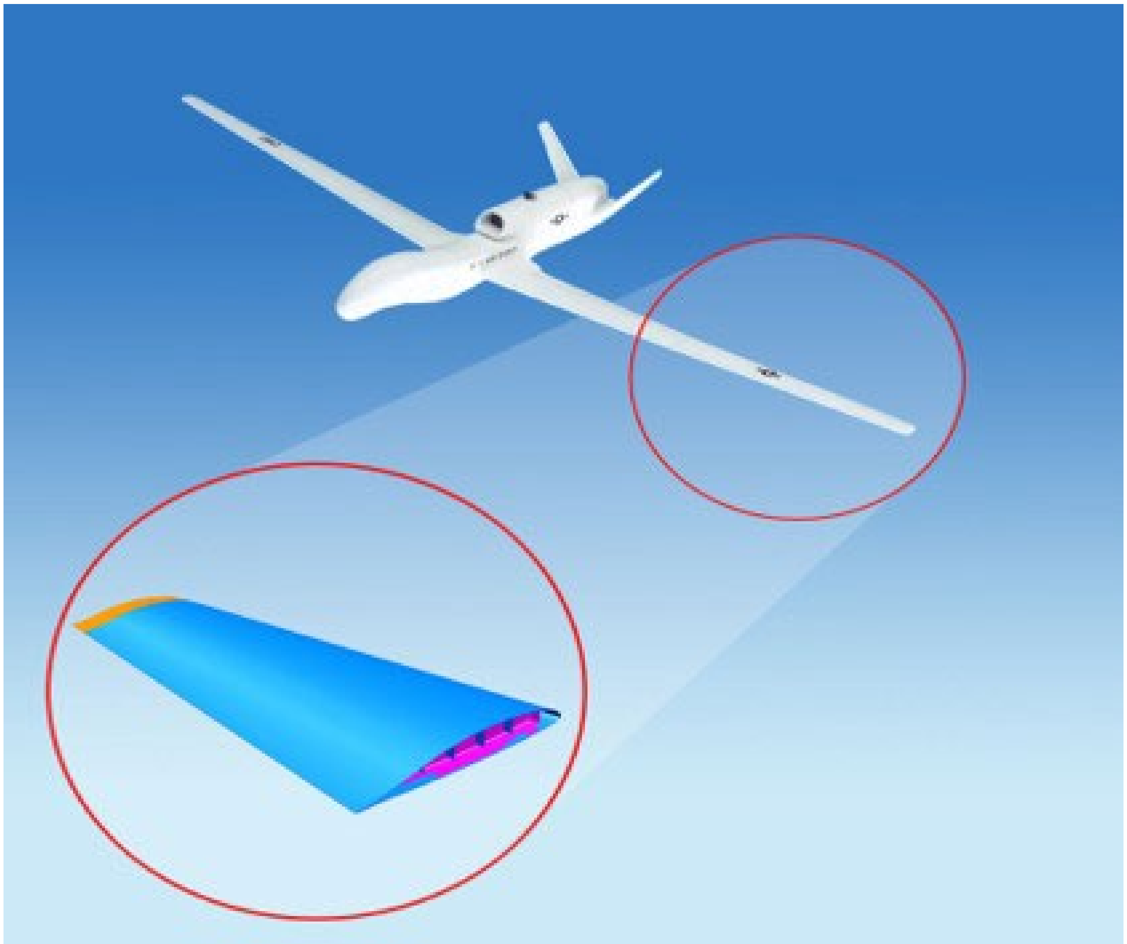

Figure 9 Global Hawk RQ-4B and Wing Tip Extension

3. CONCLUSIONS

The SQRTM manufacturing process offers unique advantages compared to autoclave manufacturing and other single-sided tooling OOA processes. Excellent laminate quality is readily achievable [1] due to the precise thickness from closed-mold processing and minimal void content, thus showing equivalent laminate properties to existing material databases. Since known and characterized aerospace prepregs can be used, FAA qualification and/or military certification can be achieved with the use of bridge panel coupon testing to show equivalency to existing material and process specifications.

The dimensional control offered by the SQRTM closed-mold approach allows unitized structures to be produced thereby reducing weight and recurring cost by eliminating bonded/fastened joints. This dimensional control also allows higher fiber volumes reducing weight compared to other manufacturing methods. Incorporation of determinant assembly features can streamline the assembly process and reduce recurring costs.

The SQRTM manufacturing process has demonstrated it can successfully produce FAA certified commercial aircraft structures. This manufacturing process is a low-risk option for those developing new electric aviation vehicles where weight, cost and cycle times are of particular importance**.**

4. REFERENCES

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