DOT/FAA/TC-23/3

Federal Aviation Administration
William J. Hughes Technical Center
Aviation Research Division
Atlantic City International Airport
New Jersey 08405

State of the Industry – Resin Infusion: A Literature Review

May 2024

Final report

U.S. Department of Transportation
Federal Aviation Administration

NOTICE

Technical Report Documentation Page

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
DOT/FAA/TC-23/3		

4. Title and Subtitle	5. Report Date
State of the Industry – Resin Infusion: A Literature Review	May 2024
	6. Performing Organization Code
7. Author(s) Wayne Huberty, Matthew Roberson, Bowen Cai, Matthew Hendrickson	8. Performing Organization Report No.
9. Performing Organization Name and Address Mississippi State University Advanced Composite Institute 110 Airport Road, Starkville, MS 39759	10. Work Unit No. (TRAIS) 11. Contract or Grant No.
12. Sponsoring Agency Name and Address Federal Aviation Administration William J. Hughes Technical Center Aviation Research Division Atlantic City International Airport New Jersey 08405	13. Type of Report and Period Covered 14. Sponsoring Agency Code

15. Supplementary Notes

The technical monitor for this JAMS research effort was Dave Stanley, ANG-E281

16. Abstract

Resin infusion processes, both resin transfer molding (RTM) and its variations, such as vacuum assisted resin transfer molding (VARTM), are poised to be more heavily adopted in transport aerospace applications due to several major advantages. This report investigated industrial applications of resin infusion and provides a general overview of many of the different types of resin infusion, the current state of these processes, automation of these processes, and novel applied technologies. Also included is a list of flying examples of resin infused aerospace parts from major original equipment manufacturers (OEMs). A short synopsis was also included about large resin infusion projects with partnerships between government, industry, and academics.

17. Key Words	18. Distribution Statement
Aircraft Composites – Resin Infusion Aircraft Composites – Simulation Aircraft Composites – Microcracking Aircraft Composites – Stitched Composites	This document is available to the U.S. public through the National Technical Information Service (NTIS), Springfield, Virginia 22161. This document is also available from the Federal Aviation Administration William J. Hughes Technical Center at actlibrary.tc.faa.gov.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	155	

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Acronyms

Acronym	**Definition**
AC	autoclave
ADMP	automated dry material placement
AFP	automatic fiber placement
ATL	automated tape layering
CAPRI	controlled atmospheric pressure resin infusion
DBVI	double bag vacuum infusion
DFCM	dynamic-fluid compression molding
FVF	fiber volume fraction
LCM	liquid compression molding
NCF	non-crimp fabrics
OEM	original equipment manufacturers
OoA	out of autoclave
PI	pulsed infusion
RTI	resin transfer infusion
RTM	resin transfer molding
SCRIMP	Seeman's composite resin infusion process
SQRTM	same qualified resin transfer molding
SRI	stitched resin infusion
TFP	tailored fiber placement
UAM	urban air mobility
UAV	unmanned aerial vehicle
VAP	vacuum assisted process
VARTM	vacuum assisted resin transfer molding
WCM	wet compression molding

Executive Summary

This report examines the state of the aerospace industry with a particular focus on resin transfer molding (RTM) and vacuum-assisted resin transfer molding (VARTM) for use in transport aircraft. This was accomplished through a public literature review which covered the existing industrial capabilities, identification of the main reasons for the limited adoption of resin infusion for primary structures, engagement through an interview process up and down the aerospace value stream, and a short academic literature review of the advantages and disadvantages of resin infusion.

Resin transfer molding (RTM) and its various processes are well-positioned to be the next technology iteration for transport aerospace primary structures. The major driver of new technology over legacy pre-impregnated (prepreg) composites is the latter's requirement for an autoclave, which use is burdened with substantial capital investment, recurring costs to heat and pressurize, and is often the bottleneck preventing high-rate manufacturing.

There are several manufacturing processes that can eliminate the autoclave, such as out-of-autoclave prepreg and RTM. While the out-of-autoclave prepreg is a smaller departure from legacy material systems, it still has many of the same drawbacks as prepregs (i.e., cold storage and out time) but also the challenges of out-of-autoclave processes, such as larger consequences of vacuum loss and difficulty with reaching low void content. Additionally, prepregs developed specifically for out-of-autoclave processing are more expensive than autoclave prepreg systems. However, some legacy systems are successfully processed out-of-autoclave.

Resin infusion processes are a larger departure from autoclave prepreg as users now perform the resin impregnation, combining dry reinforcement and resin during the manufacturing. The resin can be introduced to the dry fabric in a matched mold press, as in RTM, or using a single-sided hard mold with the dry fabric under vacuum for VARTM.

This review begins with a brief introduction to various resin infusion processes, proceeds to inform the reader of the current state of various topics related to resin infusion within industrial uses, discusses notable industrial projects using resin infusion, and ends with a review of primary literature related to resin infusion.

1 Introduction

Large original equipment manufacturers (OEM) have pledged to increase production rates to levels where existing autoclave thermoset prepreg materials will be challenged to meet production requirements within budget and manufacturing space constraints. Additionally, the Airbus Zero E blended wing body design suggests new architecture could be flying by 2035. This will necessitate complex manufacturing processes which will need to be extensively researched in the immediate future to verify these processes meet certification challenges.

Resin transfer molding (RTM) processes, and its variants, are appropriate for aircraft structures and will likely have individualized processes tailored for various applications. In its purest form, the VARTM process is best suited for large parts and complicated systems, such as wings and wing-boxes, as single-use ancillary requirements for VARTM processes, i.e., vacuum bagging, sticky tape, peel ply, etc., are most often hand laid, limiting output –although advances in automation could significantly increase the rate of production. Even without automation, parts produced via VARTM can have a higher manufacturing rate than prepregs due to the elimination of the autoclave and decreased assembly time. Many projects have demonstrated the economic viability, production rate, and capability of VARTM processes to meet performance requirements. For example, the OEM Irkut MC-21 wing produced by Aerokomposit has made a viable business case to support the use of the infusion process. This is not to suggest current aircraft prepreg parts can be completely substituted by VARTM process parts, but VARTM processes are a contender for new aircraft with undecided materials and processes.

Resin transfer molding (RTM) is a similar process to VARTM but uses matched tools and higher pressure to inject the resin into the system. The main advantages of RTM are easier automation, high rates, and the elimination of single-use vacuum ancillary equipment. A published example highlighted that approximately 80% of the individual components of a military aircraft airframe weigh less than 20 lbs. meaning these parts are “smaller” in size, which is best suited for an RTM process. RTM is being utilized in many current aircraft, mainly for trailing edge assemblies. Airbus uses RTM in the production of trailing edge assemblies for almost all their aircraft, including the new A320 flap. Some of RTM’s major limitations are the matched metallic tools are large, expensive, complicated, and the pressures associated with some RTM processes require heavy presses and robust tooling, leading to large capital expenditures.

A viable path forward could partner the VARTM and RTM processes to take advantage of both their strengths: employ a VARTM process for large, unitized structures whether a fuselage, wing, or wing-box, and use RTM for smaller structures such as flaps, doors, braces, etc. that have a higher part count. Both technologies allow for improved economics compared to automated fiber tape placement by lowering raw material costs, manufacturing costs, increasing production rates, and possibly improving performance.

The Airbus A220 wing is a significant milestone for aerospace infusion. It is produced by Spirit AeroSystems using resin-transfer infusion in a closed mold process, injecting the resin into the part while in an autoclave before pressurization. The autoclave is pressurized after the infusion is complete to aid with consolidation.

Resin infusion processes are widely seen as the next technological step for aerospace, evidenced by many large-scale research projects to further prove the technology. Some of these are USA-based projects, the Boeing RAPM project and the NASA ACT program, and the European projects, Clean Sky 2, and the Wing of Tomorrow. These heavily funded, often government-backed, multicontinental academic and industrial research programs will help the emerging technology navigate its current limitations. Spirit AeroSystems was quoted as saying that the out-of-autoclave journey was enabled by "several things that are critical to the company going forward: automation, software, support from academia and government support." Future aircraft architectures, specifically the blended wing body (BWB) architecture which is highly likely to use to resin infusion, do have their challenges: the planes will need to be large to accommodate standing room and overhead compartments, there is no good way to scale a BWB for several sizes like current tube-and-wing planes, and the advantages in drag and lift are more economical for longer flights. The likely largest hurdle for any novel aircraft architecture is making the current aircraft fleet obsolete – once a BWB aircraft is announced, will any airlines purchase the current tubular aircraft? Changing architectures will be a poor business decision until the tubular aircraft are in the black. For example, the Boeing 787 program cost of more than $30 billion was justified by an increase of 20% in efficiency over the 767 – an efficiency improvement the BWB aircraft will have to demonstrate to be a viable option.

Through-the-thickness stitched composites only have one flying example, the C-17 landing gear door – of which ~ 500 shipsets have been produced. Many programs have demonstrated the ability of stitched composites to have significant improvements for out-of-plane performance, damage arrestment, and as a manufacturing aid, but the only identified flying example of a stitched composite is for the C-17 landing gear door. Future aircraft may use stitched resin-infused parts as changing the architecture of aircraft will pose challenges to current prepreg solutions. The technology readiness level (TRL) for VARTM and RTM processes, whether stitched or not, depends on the specific structure and manufacturer: both unstitched VARTM and

RTM processes are currently flying as primary structures; however, the TRL for any other part that is not flying will be much regardless of the presence of stitching.

Any discussion of future aerospace technologies for primary structures would be remised if thermoplastics were not included. They have a similar hill to climb as does resin infusion, significant programs investing large amounts of resources, and some distinct advantages compared to both thermoset prepregs and resin-infused parts. At the time of writing, it does appear that thermoplastics are "behind" the resin infusion process regarding implementation and technology readiness. With that said, there appears a push for thermoplastics that will likely make it a capable contender soon; For example, the Stratasys ULTEM material is already NCAMP qualified, and novel demonstrator parts are being produced almost daily.

Successful implementation of large-scale infusion structures has been established and the common thread for these applications was a large-scale demonstrator proceeded initial production (known as an inverted building block approach). These large-scale demonstrators allow for risk mitigation through the identification of critical process controls before constraining the design space. Isolating and addressing these issues allows for the successful part production of the *first* production parts. Additionally, large-scale composite failure is not well predicted exclusively through coupon testing; therefore, large-scale demonstrator parts are not only critical for narrowing the design space but are also necessary to test the performance of the part.

This review begins with a brief introduction to various resin infusion processes, proceeds to inform the reader of the current state of various topics related to resin infusion within industrial uses, discusses notable industrial projects using resin infusion, and ends with a review of primary literature related to resin infusion.

2 Resin transfer molding (RTM)

In the aerospace field, weight savings to increase payload and reduce the cost and production cycle are imperative targets. To achieve these goals, composite materials have gradually been applied commercially in the aerospace field since the 1960s (Giurgiutiu, 2015; Laurenzi & Marchetti, 2012; McIlhagger, Archer, & McIlhagger, 2015) due to composite materials higher strength-to-weight ratio, fatigue resistance, and corrosion resistance (Potter K. , 1999). Over time, the role of composites has evolved from relatively small light-load components and structural parts (such as ailerons and fairings) to heavily stressed and critical parts (such as main wings and fuselage). The current commercial airliners, such as the Boeing 787, the Airbus A400 M, and the Airbus A350, are made of +50% by weight carbon fiber reinforced polymer composites, with the main wings and fuselage being largely manufactured from composite materials (McIlhagger, Archer, & McIlhagger, 2015). Among numerous methods of advanced composite manufacturing, resin transfer molding (RTM) is a production process that has high degree of automation, diverse production line designs, and mass production capabilities. Because of these, RTM has become one of the most promising processes in the field of composite material production (Robertson, 1988).

2.1 Resin transfer molding history

The resin transfer molding process shown in Figure 1 uses two hard molds: upper mold (core) and a lower mold (cavity) (Ahmadova, 2018). In production, a dry fiber "preform" (a three-dimensional shape with a defined ply schedule) is placed between the two halves of the mold which are then closed to provide a vacuum seal, vacuum is applied, and the injection commences. The overall cycle time of the process depends on the time required to prepare the preform, the injection process speed, resin cure flow rate, the resin cure kinetics. Generally, the curing time for aerospace grade epoxies is 2 hours at 350-360 °F. At the end of the process, the mold is opened, and the final product is demolded. The demolding time depends on the equipment and part size (Robertson, 1988; Ahmadova, 2018).

RTM was born in the 1930s. At that time, the process was called the Marco process and was originally used for glass fiber (Mountifield, 1969). Later, in the 1940s, the U.S. Navy began to use RTM to build 28-ft long personnel boats, which is the earliest recorded application (Spaulding, 1966). However, due to the limited technology at the time, RTM could only be used to manufacture very simple geometric shapes which limited its industrial applications (Potter K. , 1999).

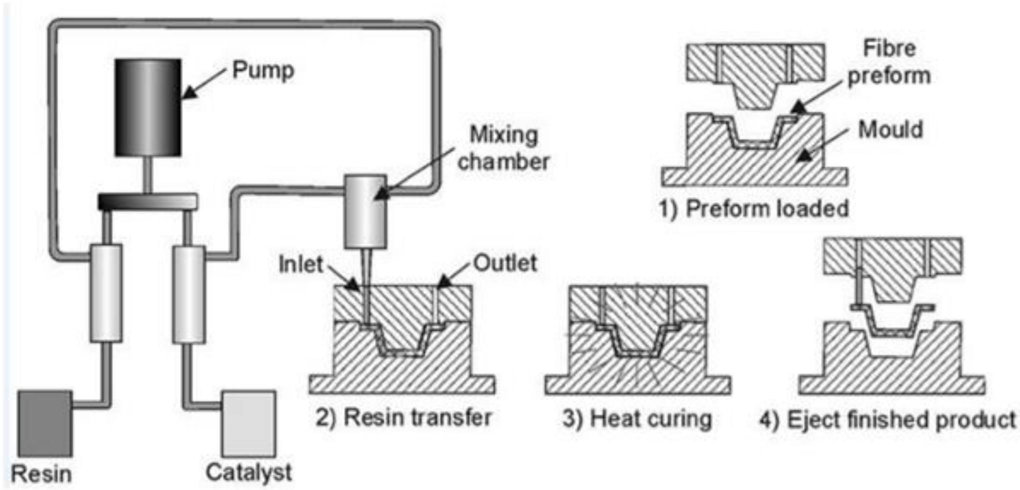

Figure 1. Resin transfer molding process cycle
Reproduced from the work of Ahmadova et al.

In the 1950s, patent records related to the RTM process began to appear. A patent issued in February 1955 describes an RTM process that can be used to manufacture airplane and automobile bodies (Potter K. , 1999). The process described in this patent is almost the same as the current RTM process.

Since the 1960s, companies have used the RTM process to produce aircraft parts such as radomes and propellers (Cooper, 1969). However, because there were many complicated operations in the RTM process at that time, it was impossible to manufacture complicated three-dimensional parts. As a result, RTM was unable to be applied on a large scale in the aerospace field in the 1960s (Potter K. , 1997).

By the 1970s, the cost of RTM began to decrease due to the improvement of mold design, injection technology, and resin properties. Meanwhile, the automated RTM production line had been put into use (Potter K. , 1997). The mainstream composite production process, autoclave (AC) prepreg, was a highly labor-intensive process, causing many companies to develop out-of-autoclave (OOA) processes, which led RTM to become one of the most promising alternative methods. In the late 1970s, high-precision RTM parts such as aeroengine compressor blades began to be designed and produced (Jones & Johnson, 1980).

In the 1980s, many companies began to design and manufacture complex composite parts to reduce aircraft weight and improve fuel efficiency (Morgan, 1989). During this period, composite material technologies such as reinforcement materials, preform production, injection molding, and fluid modeling were all greatly improved. Airbus and Boeing have designed and manufactured secondary structures (i.e., elevators, rudders, ailerons, or spoilers) for the Airbus A300 and A310, and the Boeing 757 and 767 used “graphite composites” (Das, Warren, West, & Schexnayder, 2016). Similarly, interest in RTM has gradually increased, and different variants of RTM have been developed to cope with different industrial environments and challenges (Potter K. , 1999).

2.2 Resin transfer molding advantages

RTM has many advantages compared with traditional aerospace manufacturing processes:

1. The surface finish can be adjusted to a matte or decorative finish due to a closed mold process (Potter K. , 1997).
2. Compared with traditional AC production, RTM may not require complicated finishing procedures in later stages (Woo Kim, Lee, Seferis, & Nam, 1997).
3. Thick stacks, 3D woven, stitched, or braided preforms can be processed via RTM (Gardiner G. , 2016b).
4. Various contemporary toughened resin systems can be used in RTM. Toughness can also be increased by using dry fabric with a thermoplastic veil or fabric with a binder (Forsdyke, 1984).
5. RTM does not require an autoclave, saving significant capital; however, RTM variants can be completed in an autoclave, reusing previous equipment.
6. RTM allows for isothermal tooling, significantly decreasing cycle time.
7. RTM has essentially “infinite” out-time for the dry fabric during part layup. The resin can be stored separately from the dry fabric, and often requires refrigeration; newer resins can sometimes be stored at ambient conditions. The use of dry fabric reinforcements can also lead to cost savings as prepreg scrap is much more costly than dry fabric.
8. For fixed cavity molds, the fiber volume fraction can be well controlled to ensure very consistent mechanical properties during mass production.
9. The factors that cause porosity and voids in RTM are different from those in prepreg. With proper mold design and good process control, very low or zero voids can be routinely achieved (Robertson, 1988).

10. RTM can produce very complex parts; assembled parts produced by RTM can be unitized, improving parts integration and reducing maintenance costs (Gardiner G. , 2016b).

2.3 Resin transfer molding materials

2.3.1 Reinforcements

The reinforcement fibers used for resin infusion are the same fiber systems used for prepreg systems, but they can be purchased in alternative architectures. These include woven or unidirectional (UD) architectures that can be used within any infusion process. Woven and UD fabrics are the most commonly used reinforcements.

Alternatively, non-crimp fabrics (NCF), unique to dry fabric, use a small stitch to connect multiple reinforcement plies. This allows for an increased cutting rate (as the raw number of cuts is decreased), shortens layup times, is less prone to skewed fabric direction, and has an increased through-the-thickness permeability. These stacks can be woven or unidirectional fibers and tailored to a specific application: typical fiber directions are 0/90 and/or ±45. Dry fabrics with thermoplastic veils or binders allow for automating preforming of the fabric stack in a low-temp thermoforming process. The thermoplastics or binders added can also increase the toughness of the composite systems because toughening agents added to resins are filtered by the reinforcement during the infusion, causing anisotropic toughness.

Dry tapes can also be produced for use in typical automated fiber placement (AFP) systems and can be produced in various widths, 0.25” to 1”; however, unlike prepregs that melt a resin system to bind the individual courses, the dry fabric needs a thermoplastic veil or a binder to adhere the individual courses during laydown. Typical heaters can be used as the thermoplastic melts at low temperatures, ~ 212 °F.

The various RTM processes can generally handle any of the dry fabric preforms once formed; however, automation and hand layup will have different mechanisms to get the preform ready for infusion. For example, an integrated wing skin with T-stiffeners will need to be tooled differently for a closed mold resin transfer molding or for a single-mold vacuum-assisted resin transfer process.

2.3.2 Resins

An advantage of resin infusion is classic chemistry (such as amine epoxies) with familiar cure profiles can be used. Although prepreg resins are not used during infusion due to their high viscosity, novel toughened amine epoxies with thermoplastic veiled fabrics can match current prepreg performance (Figure 49) and have viscosities usable for resin infusion (< 1,000 cP). These resins can be used as a single-part system where resin and hardener are premixed or as a two-part system where mixing occurs online during the infusion or directly before infusion. The single-part systems require refrigeration, but the two-part systems can be held at ambient conditions for up to 12 months. Typical aerospace-grade resins require a heated infusion process to lower the viscosity within the appropriate range.

Overall, the resin choice is dictated by the manufacturing method and end-use application. There is a plethora of resin choices, allowing many different fiber/resin system combinations to be tested and certified within specific manufacturing processes.

2.4 Resin transfer molding process relevant parameters

2.4.1 Processing parameters

The RTM process is controlled by interdependent variables and parameters that affect the process and the quality of the final product. Therefore, every parameter needs to be carefully determined (Park & Lee, 2011). An outline of such parameters follows (Hasan, 2020).

2.4.1.1 Inject pressure and inject speed

The injection pressure determines the injection velocity of the resin into the mold, the hydraulic pressure, and the closing forces of the mold. Consequently, the injection velocity determines the filling time and should not be too short to ensure an adequate impregnation of the fibers, and the filling cannot be slowed to the point of gelation before the complete filling of the mold. The injection pressure adjusts the distribution of the resin on the preform which affects the formation of air voids in the matrix, the appearance, and the mechanical properties of the finished product. Another phenomenon, so-called "fiber wash", i.e. the movement of the reinforcement inside the mold during the injection phase, is highly dependent upon injection pressure. In this case, the surface treatment of the fibers and the choice of the binder plays a fundamental role. If the binder dissolves too quickly in contact with the resin, then fibers under the injection pressure can move freely (Laurenzi & Marchetti, 2012).

2.4.1.2 Temperature

The temperature is an extremely important process parameter, and it requires strict control due to the relationship between injection pressure, the viscosity of the resin, and cure kinetics. When the temperature increases, the filling time decreases, and the working pressures are lower. When the temperature decreases, the viscosity of the resin increases, and it is necessary to increase the pressure to ensure the resin completely wets the preform (Laurenzi & Marchetti, 2012). The cure of the system is also affected by the temperature: increasing the temperature too rapidly or to a higher temperature to reduce cycle time can induce premature gelation, causing incomplete filling of the mold (Laurenzi & Marchetti, 2012). This becomes more of an issue as faster curing resins with lower cure temperatures are desired, requiring more reactive systems. The current resin systems inject around 200 °F and cure at 350-360 °F, a safe distance from the cure, but resin systems with a lower temperature cure, 250 °F, are already available and could cause premature gelation.

2.4.2 Product parameters

2.4.2.1 Fiber volume ratio

Ensuring the optimal volume fraction (i.e., fiber volume ratio (FVF)) is necessary to produce the desired mechanical properties of the composite (Endruweit, Gommer, & Long, 2013) and RTM processes can have a highly repeatable FVF due to the set tolerance between the core and the cavity.

2.4.2.2 Voids

Owing to the complex porous structures of woven fabrics, the progression of the flow front tends to be complicated. Additionally, a poorly placed resin inlet can lead to void formation. Voids can be divided into two classes –spherical and cylindrical pores. Spherical voids are typically located between fiber strands while cylindrical voids occur within tows between individual filaments (Park & Lee, 2011). The formation and the growth of voids cause a reduction in impact resistance, rigidity, and fatigue life, resulting in catastrophic failure of the part (Matsuzaki, Seto, Todoroki, & Mizutani, 2014).

2.5 Resin transfer molding variants

The early RTM processes had technical issues such as long production cycles, high porosity, uneven infusion, high equipment costs, short mold life, etc. Material manufacturers have been experimenting to improve the RTM process (Advani & Hsiao, 2012) and these modifications can be divided into multiple directions: injection of resin under pressure, compression molding using the mold pressure to diffuse resin into the preform, and a single hard mold and vacuum to consolidate the preform.

The common processes for injection molding are low-pressure RTM (LP-RTM) with low-pressure (145-290 psi) resin injection and high-pressure RTM (HP-RTM) with ultra-high-pressure (up to 2,175 psi) resin injection (Vita A. , Castorani, Germani, & Marconi, 2019; JHM

Technologies, n.d.; González, Vilatela, Molina-Aldareguia, Lopes, & LLorca, 2017). Various compression molding methods include compression RTM (C-RTM), wet compression molding (WCM), and Dynamic Fluid Compression Molding (DFCM). Compression molding can greatly reduce the cycle time, to within 2 minutes; however, the manufacturing process limits compression molding to produce only low-complexity parts, such as airplane body frames or wing beams (Gardiner G. , 2020b; Gardiner G. , 2016c). Vacuum Assisted Resin Transfer Molding (VARTM) is another variant of RTM that will receive more focus later in the document. Table 1 shows the RTM variants with example process parameters, output, mold types, and relative cost.

Table 1. RTM variants and example process parameters, output, mold types, and relative cost

Cost	**Mold**		**Products**				**Process**			
Cost per part	Lifetime	Materials	Voids	Part Complexity	Accuracy	Size	Fiber Content	Cycle Time	Inject Pressure (psi)	Property
High	5000-10000	Steel/Al	<2%	Complex	± 0.005″/± 0.010″	Small-Medium	Up to 70%	4-10 min	435-1,740 /Max 2,175	HP-RTM
Medium	500[2]/800-1500	Steel/Al (lower mold) FRP (upper mold)	<1%	Complex	± 0.005″/± 0.010″	S-L (25ft boat hull)	Up to 60-65%	20-60 min	145-290	LP-RTM
High	N/A	Steel/Al	<1 %	Moderate	RTM Like (± .005″/± .010″)	Small - Medium	Up to 60%	2 min	72-145	C-RTM
Medium		Steel/Al	Around 2%				Up to 65%	2 min	435	WCM (LCM)
Medium			<1%				Up to 65%	1 min	435	DFCM

Sheet annotation

1. Although the upper and lower surfaces of the parts have a mold surface, the surface finish may be inconsistent due to the different materials of the upper and lower mold.
2. To maintain a high surface finish, the upper mold needs to be polished, which will reduce the life of the upper mold.
3. The cost of C-RTM will drop sharply as output increases.
4. Huntsman mentioned in their report that all compression molding can achieve a standard “Like RTM”, but there is no more information to show a defined measurable for accuracy of compression molding.

2.5.1 Injection molding process

2.5.1.1 Low pressure-RTM (LP-RTM)

Low pressure-RTM (LP-RTM), also called RTM Lite, or Lite RTM, is a modification of the conventional RTM process. The LP-RTM process shown in Figure 2 (Vita A. , Castorani, Germani, & Marconi, 2019) was first developed in Germany in 1970 and was introduced in the United States in the 1990s (Harper, 2009). It employs lower resin injection pressure and final hydrostatic pressure during the curing cycle. A vacuum is used to clamp the molds and helps the resin flow across the preform. The standard cycle time has a duration of 30-60 minutes, with a typical injection pressure of 145-290 psi. Typical FVF ranges from 60 to 65%. This method has the advantage of using cheaper tooling and molding in comparison to traditional RTM or other closed molding processes due to the lower pressures (Davenport, Petrovich, & Sutton, , 2007).

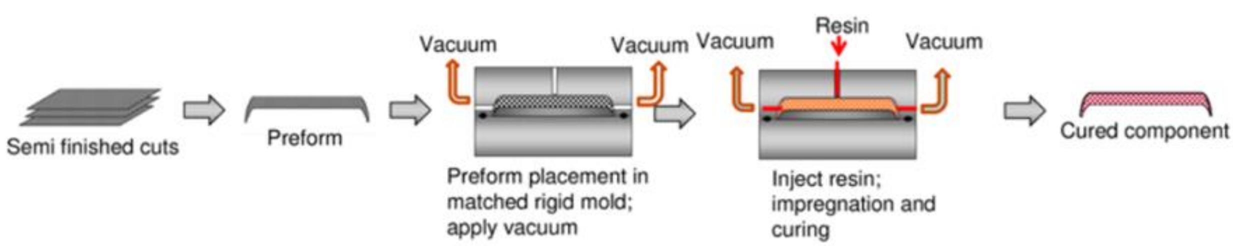

Figure 2. LP-RTM process cycle

Reproduced from the work of Marconi et al.

Davenport et al. (2007) showed composite parts produced via LP-RTM can match the mechanical properties of composites produced using higher pressure RTM. LP-RTM offers the following advantages:

Advantages

- Lower mass molds
- Improved cycle time compared to VARTM
- Potential to use cast or composite tooling
- Better temperature control than VARTM
- Reduced cost compared to AC prepregs

Disadvantages

- Lower injection pressure causes longer cycle times

2.5.1.2 Zero injection pressure resin transfer molding (ZIP-RTM)

Zero injection pressure resin transfer molding (ZIP-RTM) is a modification by JHM Technologies Inc. (MI, USA) to the lite RTM process. According to the JHM Technologies' website (JHM Technologies, n.d.), the goal of the ZIP-RTM process is to maintain negative pressure difference for the internal mold. Parts can be easily molded using two matching mold skins (the upper and lower mold halves) clamped under vacuum and then injecting the resin with a pressure below the vacuum clamping pressure.

Advantages

- Very low injection pressure
- No press required

Disadvantages

- Lower injection pressure creates longer cycle times
- Higher chance of springback behind flow front
- May have higher variation in FVF

2.5.1.3 High pressure-RTM (HP-RTM)

The diagram in Figure 3 (Vita A. , Castorani, Germani, & Marconi, 2019) shows the high-pressure RTM (HP-RTM), a technology promoted by BMW's pursuit of cycle time reduction in the 1990s. Using HP-RTM, the cycle time can be reduced to less than ten minutes for automotive parts (Gardiner G. , 2015a). High pressure, up to 2,175 psi in the mixing head and 435-1,740 psi inside the mold, are used. Typical pressures for RTM are ~ 90 psi during injection and ~ 1,100 psi during clamping (Merotte, Simacek, & Advani, 2010).

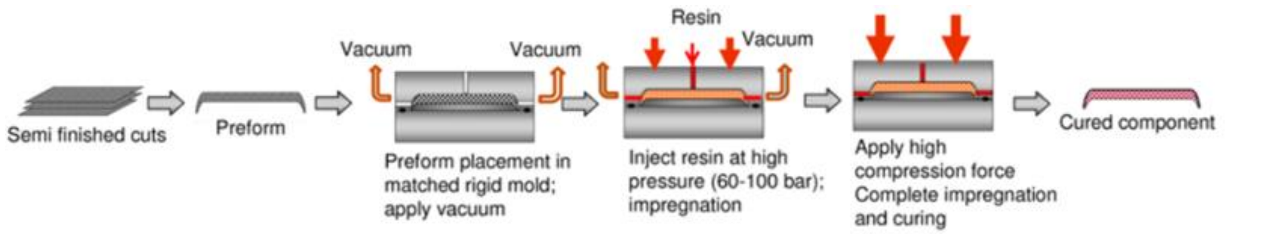

Figure 3. HP-RTM process cycle

Reproduced from the work of Marconi et al.

<u>Advantages</u>

- Very high FVF, up to 70% (Vita A. , Castorani, Germani, & Marconi, 2019)
- Fast cycle times

<u>Disadvantages</u>

- Increased equipment costs
- Higher injection pressures require more expensive tooling
- Possible fiber wash

2.5.1.4 Same qualified resin transfer molding (SQRTM)

Same qualified resin transfer molding (SQRTM) was developed and commercialized by Radius Engineering Inc. (UT, USA). SQRTM is a closed mold method that combines prepreg processing and liquid molding (CompositesWorld, 2010).

Compared to RTM, SQRTM uses a prepreg layup in place of a dry fabric preform. During injection, the resin fills all cavities with a uniform fluid pressure of approximately 100 psi along the entire edge of the part. The resin is not intended to impregnate the prepreg, but only to maintain a stable hydrostatic pressure in the mold. In the SQRTM process, the injected resin acts as a "fluid dam" to prevent the resin from squeezing out and at the same time replicate the consolidation pressure of the AC during the curing process (CompositesWorld, 2010).

Advantages

- High thermal conductivity of the production tool allows faster heating and cooling.
- Consistent FVF due to closed molds.
- Due to the use of prepreg layup, the risk of dry spots during the injection process is greatly reduced.
- Can follow current prepreg processes.

Disadvantages

- Complicated tooling
- Although current prepreg can be used, the process is not qualified.

2.5.2 Compression molding process

2.5.2.1 Compression-RTM (C-RTM)

Compression RTM (C-RTM) was funded and developed by the US Air Force in the 1990s (Yuncheng City Taiyun Building Material Co., Ltd., n.d.). The C-RTM process cycle shown in Figure 5 (Vita A. , Castorani, Germani, & Marconi, 2019; JHM Technologies, n.d.). In the C-RTM process, the dry preform is placed in the mold cavity, and the mold is partially closed to obtain a small gap between the mold surface and the fiber preform. The resin is introduced through a suitable injection point into this gap and flows easily into the mold. Once the required amount of resin is injected into the gap and the injection point is closed, the mold closes further, thereby pressing the resin into the preform to achieve the desired part thickness and volume fraction (Figure 7).

Vita et al. (2018) tested and concluded that the production time of C-RTM was much shorter than an AC process (1720 s for C-RTM and 7380 s for AC). Chaudhari et al. (2011) found the fiber volume fraction, mechanical strength, and interlaminar shear stress of C-RTM parts are comparable to those of RTM.

Although C-RTM was originally funded by the US Air Force for research and development, it is widely used in automobile body manufacturing (Yuncheng City Taiyun Building Material Co., Ltd., n.d.). Techni-Modul Engineering (TME) has cooperated with material supplier Hexcel to apply a new generation C-RTM technology in the OPTICOMS project, part of Clean Sky 2, to produce an I-beam and a rib for a composite wing. The Clean Sky 2 OPTICOMS rib part shown in Figure 4 (Gardiner G. , 2020b) are expected to be put into mass production in 2025. The advantage of C-RTM lies in an approximately 90% faster infusion time for the OPTIMCOMS parts. The I-beam stringer with a length of 35 in and a height of 5.9 in required only 5 minutes to infuse, compared to 60 minutes for the legacy manufacturing method (Gardiner G. , 2020b). Additionally, the injection time for a 27.5 in-long and 7.9 in-wide wing rib in the OPTICOMS project was reduced from 40 minutes to 5 minutes (Gardiner G. , 2020b).

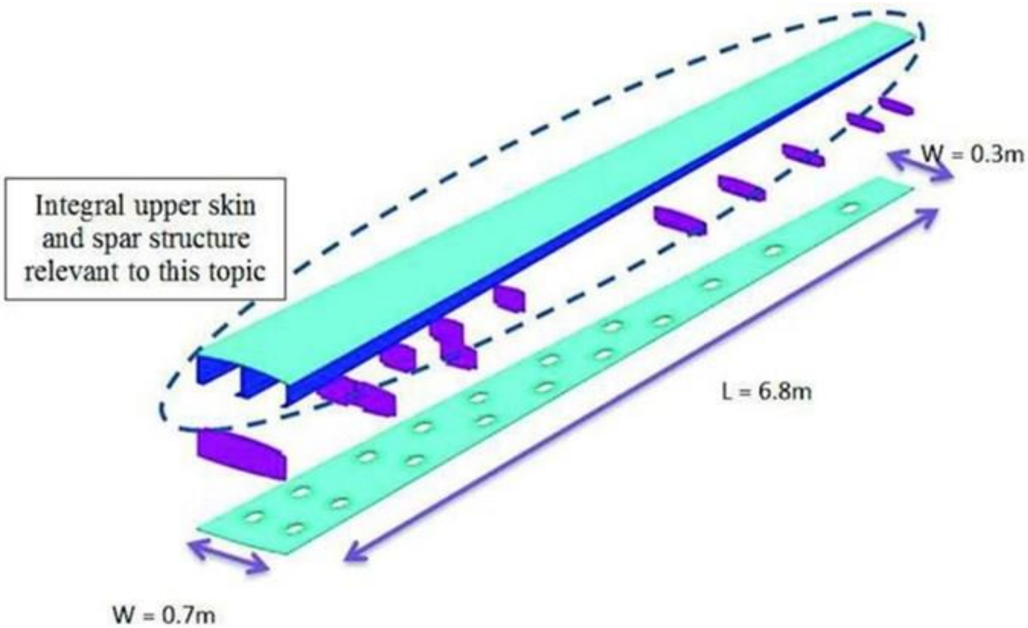

Figure 4. Clean Sky 2 OPTICOMS rib part

Reproduced from CompositesWorld

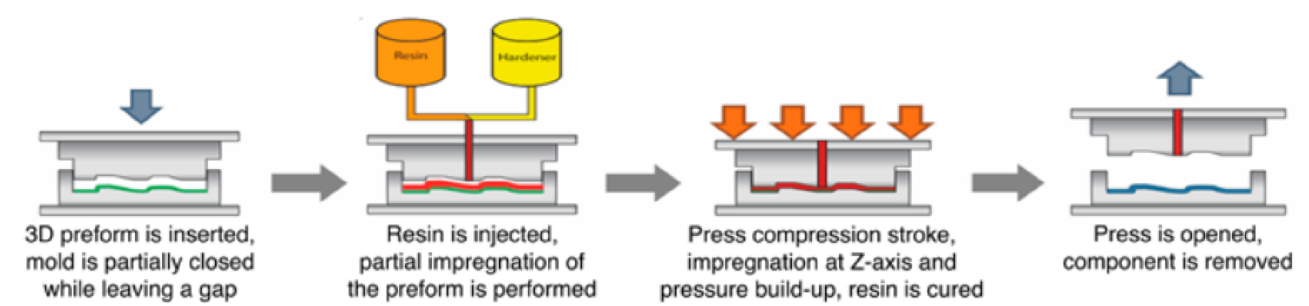

Figure 5. C-RTM process cycle

Reproduced from the work of Marconi et al.

Advantages

- Lower pressure injection than RTM (80-90 psi), causing less fiber wash
- Fast cycle rates
- Lower equipment costs than HP-RTM

Disadvantages

- Requires tighter control over mold cavity distance during injection

2.5.2.2 Wet compression molding (WCM)

Wet compression molding (WCM) is one of the fastest composite manufacturing processes currently available for mass production. This process eliminates the injection stage by introducing the resin onto the preform outside of the RTM press, resulting in shorter on-tool time. It also provides additional freedom to formulators because the resin used in this process does not require the chemical latency needed for typical RTM (Ghazizadeh, Kincaid, & Costantino, 2018).

Advantages

- Addition of the resin occurs outside of the press
- Lowest on-tool time (Ghazizadeh, Kincaid, & Costantino, 2018)

Disadvantages

- Less complex parts can be produced
- Increased chance of lower FVF and voids (Ghazizadeh, Kincaid, & Costantino, 2018)

2.5.2.3 Dynamic fluid compression molding (DFCM)

Huntsman introduced a wet compression molding process known as Dynamic Fluid Compression Molding (DFCM) that combines the fast production rate of WCM and the high quality of HP-RTM (CompositesWorld, 2016). The main difference between DFCM and WCM is that the DFCM mold is closed and held under vacuum when the mold is closed (Figure 6), which can use higher pressure to produce parts, increase fiber volume, and reduce dry spots (CompositesWorld, 2016). The process can reduce cycle times to as low as one minute and eliminates the need for post-curing for non-aerospace applications. The Huntsman ARALDITE® resin system exhibits excellent flowability yielding parts with fiber volume contents of more than 65% and virtually no porosity even on deep-draw and highly contoured designs (Harms, n.d.). Huntsman claimed DFCM can achieve complex geometry production (Medium draw or >2.5D), but there is not much information indicating that DFCM can produce parts with a level of complexity similar to HP/LP-RTM (CompositesWorld, 2016; Gardiner G. , 2016c).

Ghazizadeh et al. (2018) conducted detailed research and testing on DFCM samples, and provided a comparison between DFCM and other RTM variants:

Advantages

- Lower cycle time than HP-RTM
- Capable of <1% voids
- Higher complexity parts compared to WCM

Disadvantages

- Capable of lower complexity parts compared to other RTM variants

2.5.3 Vacuum-assisted resin transfer molding

2.5.3.1 Comparing RTM and VARTM

Vacuum-Assisted RTM (VARTM) while still a variant of RTM, is significantly different than the other RTM variants previously discussed. VARTM does not use a closed mold process, but rather a single-sided hard tool, matched with a soft tool, often a vacuum bag; therefore, the compaction is solely due to vacuum pressure, and there is no additional pressure available from a press. Consequently, the capital costs for VARTM are lower than RTM by eliminating the press. It is expected larger, integrated structures, i.e. wing boxes, will utilize a VARTM process and smaller parts, i.e. flaps, will use RTM due to the cost of tooling and presses; however, the increased rate requirements for commercial aerospace may drive companies to RTM for large structures for the increased rate capability.

Several different modifications can be implemented to improve the VARTM process. Flow assistance like channels or flow media can be introduced to lower injection times and prevent dry spots by easily moving resin to areas with high susceptibility for dry spots (Leclerc & Ruiz, 2008). Resin degassing allows for tight control over porosity by removing trapped gases. A secondary bag may reduce fiber “spring back” (Patent No. 7,931,458 U.S. Patent and Trademark Office, 2011) behind the flow front, although double bagging does not seem to have a consensus as to the efficacy (Patent No. 8,356,989 U.S. Patent and Trademark Office, 2013; Li W. , 2004; Alam Khan, Mahmood, Ahmed, & Day, 2013; Rigas, Mulkern, Walsh, & Nguyen, 2001).

2.5.3.1.1 Advantages and disadvantages of VARTM

<u>Advantages</u>

- No press required
- Lowers capital costs compared to RTM by only using one hard tool
- Low voids/porosity (< 2%)
- High FVF (60-80%) (Witik, et al., 2012) by weight
- Many types of tooling are supported
- Accurate dimensional accuracy (Lawrence, et al., 2008; Du, et al., 2013; Lee, Wu, Hsu, & Chung, 2006)

<u>Disadvantages</u>

- Maximum compaction pressure is limited to atmospheric pressure
- The vacuum bag side does not produce a mold-quality surface
- Single-use consumables
- Possible fiber spring-back behind the resin flow front
- Risk of incomplete wetout of the dry fabric preform

2.5.3.1.2 Performance comparison VARTM vs RTM

There have been multiple experiments completed that compare the differences between VARTM and RTM (Vengalrao, Kumar, Ravi Shanker, Srinivasababu, & Kiran Kumar Yadav, 2017). The main areas of consideration are impact strength, void volume, and other related parameters. Table 2 adapted from the work of Vengalrao et al. (Vengalrao, Kumar, Ravi Shanker, Srinivasababu, & Kiran Kumar Yadav, 2017), shows the comparison of void volume in VARTM and RTM produced laminates for different vacuum and injection pressures. Table 3, adapted from the work of Vengalrao et al. (Vengalrao, Kumar, Ravi Shanker, Srinivasababu, & Kiran Kumar Yadav, 2017), shows the relationship between IZOD impact strength and void volume at different pressures for the RTM and VARTM processes, respectively. Likely the inability to have < 2% voids for the VARTM processes stems from the "high" pressure during infusion – typically vacuum pressure would be 0.05 ± 0.05 psi during infusion and almost 0 psi/min leak down rate. Additionally, the VARTM sample shows how important vacuum levels are for VARTM processes. The pressures used in the RTM processing are quite low but still produced low void structures.

Table 2. Void volume % for laminates produced by RTM and VARTM

RTM		VARTM	
Injection Pressure (psi)	**Void volume (%) for laminates in RTM**	**Vacuum Pressure (psi)**	**Void volume (%) for laminates in VARTM**
28.4	1.63	1.9	3.39
35.5	1.6	3.9	12.93
42.64	1.54	5.8	32.21
49.7	1.48	7.7	36.50
56.9	1.71	9.7	36.91

Table 3. Impact strength for laminates produced by RTM and VARTM

RTM		VARTM	
Injection Pressure (psi)	**IZOD Impact strength of the specimen with 6 layers (J/m)**	**Vacuum Pressure (psi)**	**Impact strength of the specimen with 6 layers (J/m)**
28.4	430.5	1.9	113
35.5	447.58	3.9	98.52
42.64	467.16	5.8	93.35
49.7	468.19	7.7	91.41
56.9	387.09	9.7	72.52

2.5.3.2 Comparison of named vacuum assisted infusion techniques from Bickerton

The quantitative comparisons in section 2.5.3 are for flat panels produced in a study from Van Oosterom et al. (2019). These data may change for more complex geometries.

2.5.3.2.1 Seeman's composite resin infusion molding process

Seeman's Composite Resin Infusion Molding Process, SCRIMP, is the most widely used vacuum bag process and uses distribution media to allow for easier flow of the resin, increasing the speed of the infusion: SCRIMP decreases resin flow time by 80% by adding the flow media. The significantly higher permeability for the flow media compared to the reinforcement, allows for strategic race tracking of the resin to aid the wet out of the reinforcement. SCRIMP has a lower vacuum pressure drop than traditional VARTM without flow media, a lower thickness variation due to a lower vacuum pressure drop, and uses more resin than the typical VARTM process due to the filling of the distribution media.

2.5.3.2.2 Vacuum-assisted process

The Airbus/EADS Vacuum Assisted Process (VAP) uses a semipermeable membrane in place of distribution media to keep the laminate thickness constant during the filling stage. VAP helps reduce dry spots and increases the wetting of resin, lowers the void content, and increases fiber volume fraction by counteracting the "resin lockout" of the vacuum outlet when resin can enter the vacuum outlet and "cut off" the vacuum source (Bodaghi, et al., 2020; Hexcel Corporation, 2020). VAP has a lower infusion flow time compared to SCRIMP by 13% and a lower laminate pressure drop rate during the post-filling stage (Witik, et al., 2012).

2.5.3.2.3 Controlled atmospheric pressure resin infusion

The Boeing Controlled Atmospheric Pressure Resin Infusion (CAPRI) has two main foci: increased fiber nesting and lower injection pressure to prevent thickness gradients. Nesting is increased through multiple vacuum cycles and is more important in the weft direction than in the warp direction; this is because the warp ends are heavily compacted and crimped, which possibly increases permeability in the weft direction compared to the warp direction. CAPRI can produce less than 1% thickness gradients, 5% higher fiber fraction than SCRIMP, and 8% lower laminate thickness compared to SCRIMP. However, the laminate pressure drops very quickly during cure and may cause voids (Niggemann, Song, Gillespie, & Heider, 2008). There is a 60% higher infusion time for the CAPRI process when compared to the SCRIMP process, presumably due to the lower pressure of the resin pot. The VARTM, SCRIMP and CAPRI, VAP, DBVI, and PL processes are shown in Figure 6 (Van Oosterom, Allen, Battley, & Bickerton, 2019).

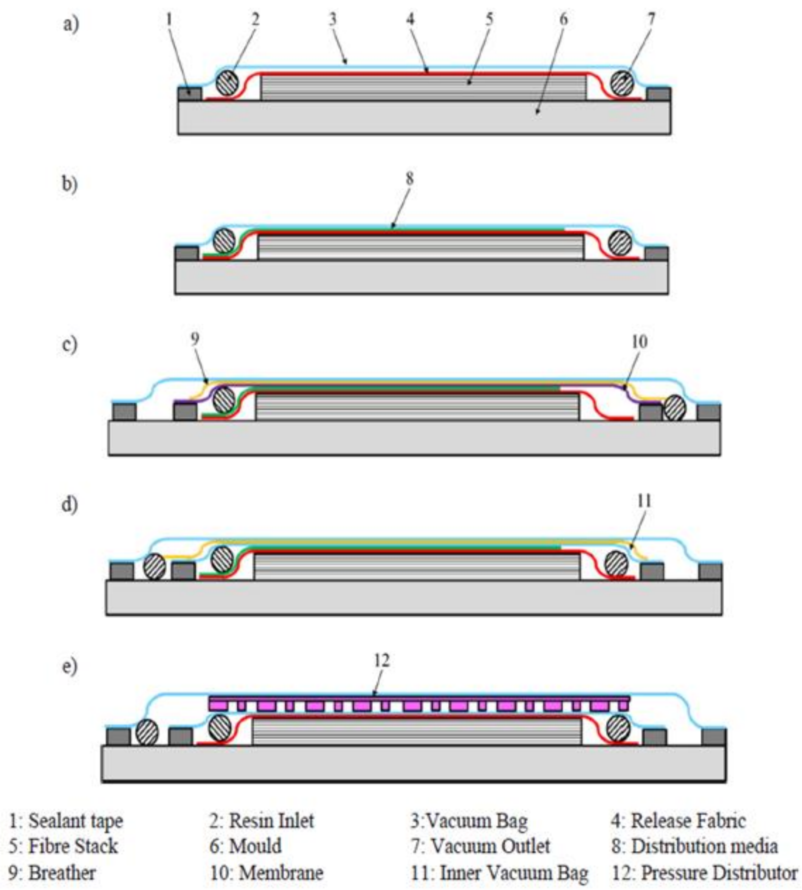

Figure 6. Schematic of processes

a) VARTM b) SCRIMP and CAPRI c) VAP d) DBVI e) PL

Reproduced from the work of van Van Oosterom et al.

2.5.3.2.4 Pulsed infusion

Pulsed infusion (PI) uses two vacuum bags with a lower vacuum pressure in the top bag to create resin channels during the infusion and then eliminates the channels by increasing the vacuum pressure. PI provided an increase of flex modulus of 9% and flexural strength of 24%. PI has a slower and less efficient infusion, with 190% of the SCRIMP resin fill time. It has 27% more resin than the VARTM process, leading to an increase in thickness of 223%, 79%, and 28% compared to VARTM at the inlet, center, and outlet respectively. PI also has a 26% variance in thickness between the inlet and outlet.

2.5.3.2.5 Double bag vacuum infusion

The double bag vacuum infusion (DBVI) process uses a very similar setup to SCRIMP but adds a second vacuum bag to help consolidate the part. Typically, with a single vacuum bag, the resin flow front can cause a loss of pressure difference between the infused part and the atmosphere, decreasing the fiber volume fraction. A second bag allows for continual and equal consolidation pressure during the entire infusion process to increase the FVF.

High resin flow rates have been shown to cause macro-voids within fiber tows due to resin flow differences between inter and intra-tows. Intertows (tows perpendicular to the direction of resin flow) can cause bubbles to form and slows wetting. A fast resin flow front (SCRIMP and VAP) can cause bubbles.

The key to being able to produce large, one-off structures by resin infusion with minimal risk of significant deviations of laminate characteristics from the design is being able to accurately select process parameters to achieve the target fiber volume fractions based on compaction characterization of the laminate. Table 4, adapted from the work of Van Oosterom et al. (2019) and Table 5, adapted from the work of Bodaghi et al. (2020), show two different studies comparing various RTM methods. Distribution media appears to increase the variation in the fiber volume fraction between the inlet and outlet; however, a short beam test shows no difference between samples taken from the inlet and outlet areas (Govignon, Bickerton, Morris, & Kelly, 2008). Short beam strength and fracture toughness increase with decreasing fiber content because of the increased plastic deformation energy dissipation in thicker resin rich interlaminar layers present in low fiber volume fraction composites (Davies, Casari, & Carlsson, 2005).

Table 4. Measured fiber volume fractions for each manufacturing method

	Process	**Fiber Volume Percentage**
VARTM	FVF Inlet	47%
	FVF Outlet	49%
SCRIMP	FVF Inlet	47.7%
	FVF Outlet	47.9%
DBVI	FVF Inlet	45.4%
	FVF Outlet	47.5%
VAP	FVF Inlet	50.2%
	FVF Outlet	50.5%
CAPRI	FVF Inlet	51.8%
	FVF Outlet	52.2%
PI	FVF Inlet	39.5%
	FVF Outlet	48.7%

Table 5. Comparison of fiber volume fraction calculations using a burn-off technique and thickness measurements

Manufacturing Method		**Average Fiber Volume Fraction**					
		Weight Loss	**CV (%)**	**Local Part Thickness**	**CV (%)**	**FVF (%)**	**Void Content**
VAP	Run 1	56.15±0.37	.065	55.83±0.32	0.57	56	1.53
	Run 2	55.4±1.04	1.87	53.38±0.33	0.61	53.3	0.755
	Run 3	52.79±1.39	2.63	54.76±1.63	2.97	55.4	1.84
	Run 4	53.89±1.2	2.22	52.88±0.79	1.49	53.2	2.55
DBVI	Run 1	56.55±0.38	0.67	57.3±0.85	1.48	57.3	2.77
	Run 2	58.73±0.74	1.26	60.19±0.61	1.01	60.5	3.57
	Run 3	56.01±1.36	2.42	55.07±1.7	3.08	55.1	3.52
	Run 4	56.4±1.37	2.42	55.13±1.6	2.90	55.5	4.55
CAPRI	Run 1	62.96±0.9	1.42	61.38±0.58	0.94	61.5	2.48
	Run 2	60.86±1.11	1.82	61.21±0.34	0.55	61.4	1.54
	Run 3	54.16±0.98	1.8	54.97±2.3	4.18	55.4	3.01
	Run 4	53.52±0.98	1.83	54.88±1.3	2.36	55.4	2.41
HP-RTM	Run 1	60.35±1.82	3.01	60.28±0.9	1.49	60.5	0.659
	Run 2	63.81±0.48	0.75	63.22±0.72	1.13	63.6	0.388
	Run 3	61.06±1.6	2.62	63.21±1.2	1.89	63.4	1.62
	Run 4	62.25±0.93	1.49	62.23±0.83	1.33	62.5	2.16

2.5.4 Environmental impact of various RTM variants

Environmental issues have an important consideration in the production of composite materials. Compared with metals, composite materials are recycled at a much lower rate. Therefore, in recent years, reducing the environmental impact of the composite material production process has become a key research topic.

Witik et al. (2012) identified the AC molding process is three times more energy-intensive compared to RTM techniques. Marconi et al. (2019) used the ReCiPe method to investigate and compare the environmental impacts of three alternative manufacturing processes for producing CFRP. The primary objective of the ReCiPe method is to transform the long list of life cycle results into a limited number of indicator scores. These indicator scores express the relative severity of an environmental impact category (Figure 7). The C, LP, and HP in Figure 7 (Vita A. , Castorani, Germani, & Marconi, 2019) all stand for compression-RTM, low-pressure RTM, and high-pressure RTM, respectively. The mold is the single highest producer of environmental impact for closed molded RTM. The raw materials used to make molds can be recycled, which can significantly reduce the overall environmental impact. Compression-RTM is the most environmentally friendly RTM process variant, followed by low-pressure RTM and high-pressure RTM. Shortened curing time (if compared with LP-RTM) and a lower injection pressure (compared with HP-RTM) provide a significant reduction in energy consumption, thereby reducing the impact on the environment (Vita A. , Castorani, Germani, & Marconi, 2019).

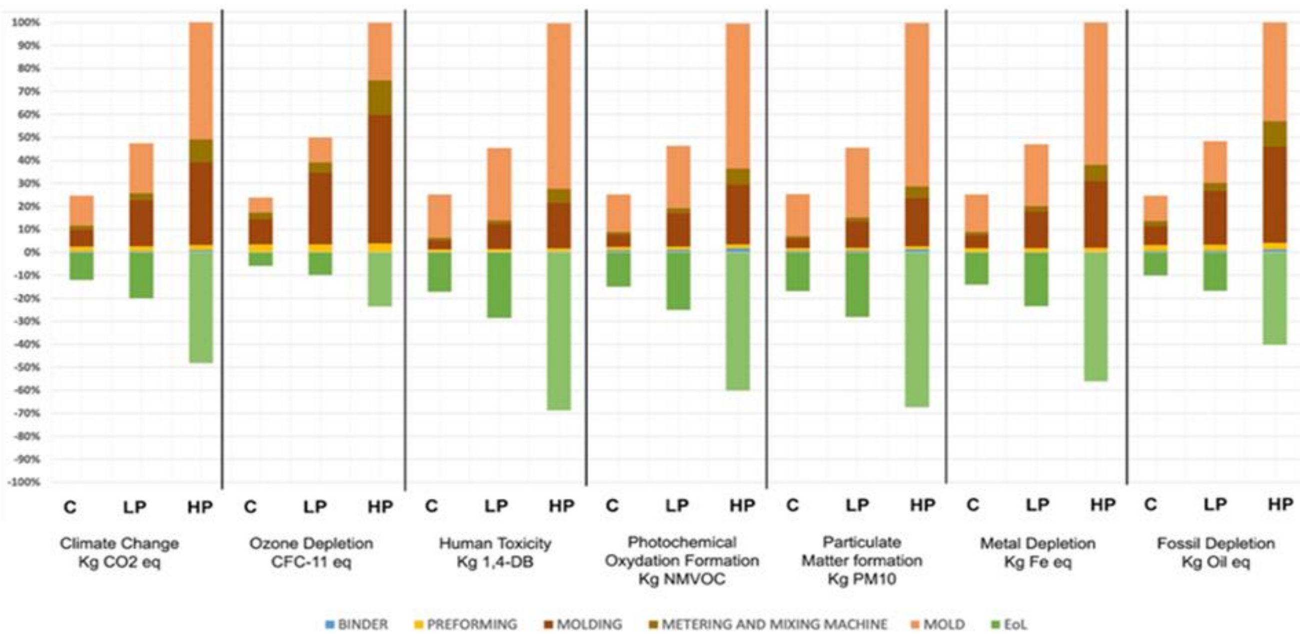

Figure 7. Comparison of RTM variants in terms of ReCiPe mid-points

C is compression-RTM, LP is low-pressure RTM, and HP is high-pressure RTM

Reproduced from the work of Marconi et al.

2.5.5 Pseudo-market value chain

A pseudo-market value chain is included below for transport airplane applications. This is not an exhaustive list but highlights specific companies that fall along the resin infusion value stream, along with some competing technology such as out-of-autoclave (OoA) prepreg. The long list indicates the health of the supply chain to support resin infusion.

2.5.5.1 Large-scale public entities

- Cooperative Research Centre for Advanced Composite Structures
- National Composites Center
- German Aerospace Center
- National Institute of Aviation Research (NIAR)

2.5.5.2 Aircraft producers

- Boeing
- Airbus
- European Aeronautic Defense and Space Co (EADS)

2.5.5.3 Aircraft parts producers

- GKN Aerospace
- Ratier-Figac
- Alenia Aeronautica
- Triumph Group
- Kawasaki Heavy Industries
- Spirit AeroSystems
- Fuji Heavy Industries
- Korean Air Aerospace
- Latecoere
- GE Aerospace
- Rolls Royce
- Goodrich
- Hawker de Havilland
- Albany Engineered Composites
- Aircelle
- Electroimpact

- Premium Aerotec Group
- FACC AG
- Radius Engineering
- CFM International
- Pratt and Whitney

2.5.5.4 Carbon fiber producers

- SAERTEX
- Hexcel
- Toray Industries
- Torayca
- Teijin Ltd
- Gurit
- Advanced Composites Group Ltd

2.5.5.5 Assembly

- NORDAM
- Vought Aircraft Industries Inc

2.5.5.6 Resin producers

- Solvay
- Hexcel
- Alpharetta
- Huntsman Advanced Materials

2.5.5.7 Core materials

- Rohacell PMI
- Hexcel

2.5.5.8 Disposables

- DuPont
- Gore-tex
- Airtech International

2.5.5.9 Distribution fiber placement

- CompositesOne

2.5.5.10 Fiber placement

- Ingersoll Machine Tools
- Coriolis
- Automated Dynamics
- MAG Composite Technologies
- MTorres
- ElectroImpact
- Fives

2.5.5.11 Fiber braiding

- Airbus
- Albany Engineering
- SGL Kümpers
- A&P Technology

2.5.5.12 Cutting and kitting

- ABB Group
- Web Industries
- Airborne

2.5.5.13 Injection machines

- Composite Integration Ltd.
- ISOJET Equipment
- Radius Engineering

2.5.5.14 Preforms

- Pinette Emidecau Industries
- Airborne
- Radius Engineering

3 Automation of resin infusion processes

This literature review was supplemented by a market interview process that identified and quantified problems of the market preventing the adoption of resin infusion (DOT/FAA/TC-23/1). The automation of resin infusion processes has been identified as an important and dissatisfied area and has the potential to generally improve quality and lower cost (Das, Warren, West, & Schexnayder, 2016). It is also suggested to be the most important part of high-rate manufacturing (Fauster, Schillfahrt, Hueber, & Schledjewski, 2017). Automation has been heavily adopted for current aircraft material systems, i.e., automated tape layering (ATL) and automated nondestructive inspection (NDI), but the layup process can be different between prepreg and resin-infused materials -- although there is the capability to retrofit current prepreg ATL machines for dry fiber. One company interviewed even suggested that trained technicians familiar with prepreg layup are unable to easily transition to the layup of the dry fabric as the fabric “freaks them out”. Automation can also address some of the quality challenges when laying down dry fabrics and infusing the resin. Automation requires individual attention as the economics of automated processes can vary for different structures -- no single process is best suited for every part (Fauster, Schillfahrt, Hueber, & Schledjewski, 2017).

3.1 Manual preforming

Dry fabric preforms are unique to resin infusion and present application difficulties due to the lack of experience and manufacturing maturation for these preforms. The most common process of making a perform is manual layup where the plies of fabric are cut and laid manually onto a tool. While this is not a significant departure from the current prepreg layup process, the lack of tack for dry fabrics can allow layers of fabric stack to slide past one another, which can cause buckling, wrinkling, or warping of the carbon tows. These possible issues can lead to variable and uncontrolled performance and/or quality issues for the parts. However, one advantage of the ability of the fabric to slide is that mistakes during the layup sequence can easily be rectified, a distinct departure from prepregs and OoA prepregs, as long as they are identified before infusion.

Thermoplastic binders on the dry fabric are also unique to the dry fabric preforming process. These binders can be added to the preform to prevent any slipping when doing the infusion and/or during consolidation (Hexcel Corporation, 2020). Binders have two ways to enter the process: incorporation into the fabric as a backing layer or sprayed onto the dry fabric preform (Hexcel Corporation, 2020). While these binders make the process of transferring the dry-fabric preform into the final tool/mold easier, they can cause issues in the system due to low resin compatibility leading to decrease performance for properties dependent upon resin/matrix interactions (Danobat, n.d.; Meade & Joseph, 2019).

3.2 Automated preforming

3.2.1 Automated fiber placement (AFP)

Automation can address poor quality, variability, and cost due to hand layup: variability being a particular challenge for hand layup (Budwal, Kasper, Goering, & Ward, 2020; Endruweit, Gommer, & Long, 2013). Precedence shows manufacturing costs can decrease by 30% and cycle times can decrease by 50% for automated pick-and-place compared to rolled fabrics (Ilcewicz & Ashforth, 2020). These statistics support the move of the aerospace industry to high-rate manufacturing, which has already been identified as a critical path forward (Gardiner G. , 2020a; Meade & Joseph, 2019).

An example of an automation process for resin infusion is using automated fiber placement (AFP). AFP is a similar process to ATL in that it can lay down fabric in different thicknesses and often current ATL machines need subtle upgrades to handle dry fabric (Gardiner G. , 2016a). A unique example of AFP is called tailored fiber placement (TFP) which allows for specific tows to be controlled in the exact directions to best aid performance rather than legacy unidirectional or bidirectional fabric typical layup of ± 90° or ±45° (Gardiner G. , 2016a). Figure 8 shows an example of TFP technology (LayStitch Technologies, n.d.) being pioneered by companies like RAMPF and LayStitch Technologies.

LayStitch shows how TFP can steer the tows in unusual directions, providing additional strength in the load directions and it can also be automated, increasing throughput and repeatability (Gardiner G. , 2020a; Gardiner G. , 2016a). As an example, TFP can improve stiffness, buckling strength, notch and cut-out sensitivity, delamination, and increase damage tolerance by being able to steer the tows as low as 5° increments. When making a mountain bike brake booster, woven prepregs weighed 20% more than a TFP part with only 30% of the absolute stiffness (González, Vilatela, Molina-Aldareguia, Lopes, & LLorca, 2017). TFP has also been used on the Airbus A350 carbon window frame (see section “Parts of Planes with Infused Composites” for more information) (Fristedt, 2012).

Figure 8. Example of tailored fiber placement
Permission from LayStitch, LLC

Tow steering during AFP can also place tapes of fabric in directions not typically possible. Instead of a typical 90° difference between layers, tow steering can much more granularly control the fiber direction to lead to much higher performance by dispersing the load (Figure 9). An example of fiber placement of a tape and compression performance is also shown in Figure 9 (Gardiner G. , 2015a).

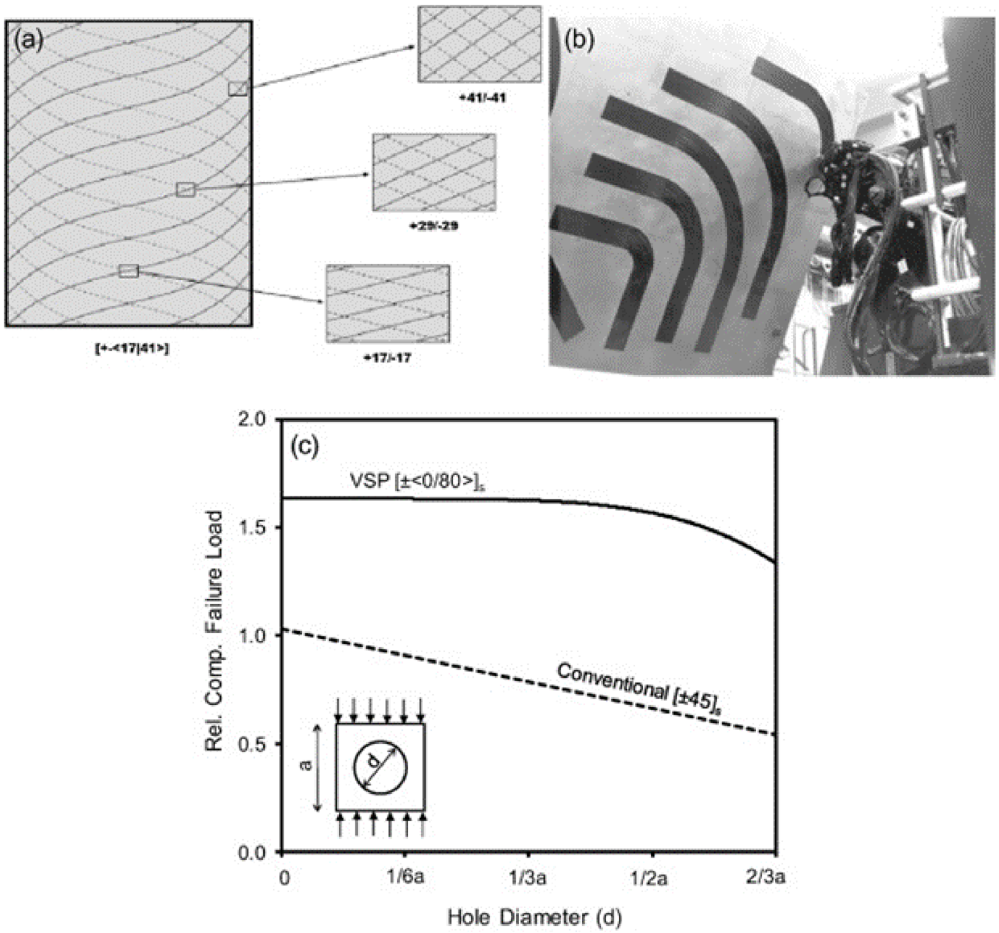

Figure 9. Example of fiber placement of a tape and compression performance
Reproduced from the work of Llorca et al.

Using automated techniques, like TFP, the fabric can be laid into a near net shape. Large structures are best suited for AFP because they often do not have high curvature or complexity (González, Vilatela, Molina-Aldareguia, Lopes, & LLorca, 2017). AFP also has less material waste than manual processes; however, smaller, complex parts are more difficult and less amenable to AFP (Fauster, Schillfahrt, Hueber, & Schledjewski, 2017).

Other technologies are maximizing the throughput by laying large ply widths. An example of this is the Danobat system being used in the Clean Sky 2 project to produce upper wing skins of a C-295 aircraft using automated dry material placement (ADMP). Danobat claims laying speeds of > 100 m/min, laying fabric up to 2 meters wide, and increasing the throughput 10x compared to AFP (CompositesWorld, 2019b). Not only is this process significant due to automation and speed, but it can also meet the performance of the current prepreg part (Danobat, n.d.).

3.2.2 3D stabilization of preform

There are several methods to produce a 3D stabilized preform, a requirement for complicated tooling with vertical surfaces or deep draw.

2D Braiding:

2D braiding is the typical carbon fiber weave where tows are intertwined between each other, commonly ± 90°. The crimps in the braided material cause fiber waviness and cause a permanent decrease in material properties (Hexcel Corporation, 2020). Changing the weave type from smaller to larger distances between crimps will improve the mechanical properties, such as in spread-tow fabrics (Fauster, Schillfahrt, Hueber, & Schledjewski, 2017). The ability of the dry fabric reinforcement to have tailored properties (i.e. in the transverse direction) is limited by the angle of the 2D braiding (Fauster, Schillfahrt, Hueber, & Schledjewski, 2017).

3D braiding:

Another method for making an automated preform is through winding the reinforcement tows around a mandrel or tool (Figure 10), called 3D over braiding. Figure 10 is an example of 3D braiding from IACMI (IACMI, n.d.). This is not possible for dry fabrics unless a binder or thermoplastic is melted to hold the reinforcement in place. Some advantages of 3D braiding are the through-the-thickness performance and improved load distribution, fewer steps in preparing the 3D preform compared to the 2D preform, fewer areas for high resin concentration, increased inter-laminar stiffness and stress, and a versatile design (Fauster, Schillfahrt, Hueber, & Schledjewski, 2017). T-structure 3D braiding was used for the inlet duct of the F-35 and was able to save 80 lbs, $200,000 per duct, and eliminated 95% of the fasteners (Budwal, Kasper, Goering, & Ward, 2020; Fauster, Schillfahrt, Hueber, & Schledjewski, 2017).

Figure 10. Example of 3D braiding
Permission from IACMI

3D woven:

3D materials can also be produced by weaving a three-dimensional part in complicated architectures. Fabrics can be formed to near net shape with considerable thickness, up to ten cm in thickness (CompositesWorld, 2018). More than one layer of fabric is woven at the same time, and binder yarns interlace the different layers. Several different woven techniques that can be used to help increase the thickness of the composite: two examples are angle interlock three-dimensional weaves and bifurcation. 3D weaving can be used for rotors, nose cones, nozzles, mounts, and aircraft frameworks. Fabrics that are made from 3D weavings are ideal for out-of-plane loading applications, have a high formability, and have little or no crimp (CompositesWorld, 2018). GE Aerosapce uses 3D braided materials for the CFM LEAP engines (CompositesWorld, 2016).

3.2.3 Hot drape forming

Hot drape forming is a low-pressure, low-temperature process to adhere the individual fabric stacks to one another through a thermoplastic binder or veil. A compacted, near-net shape preform is produced by heating the ply stack on a near-net tool with a flexible bag placed over the tool (Gardiner G. , 2021b). MTorres used this technique to produce the preform as a part of the Clean Sky 2 project. An example of the thermoforming machine is shown in Figure 11.

Figure 11. Example thermoforming machine
Provided by Techni Modul Engineering

3.2.4 Continuous preforming

A way to move beyond batch preforming processes is to use continuous preforming. Figure 12 is an example of continuous preforming (Fauster, Schillfahrt, Hueber, & Schledjewski, 2017). This process feeds a dry fabric stack into a system that acts as a conveyer belt, molding the dry fabric and forming it into the final preform. This method can produce preforms as fast as 236 in per minute and can have constant or variable thicknesses, along with curvature (Fauster, Schillfahrt, Hueber, & Schledjewski, 2017). Breaking complicated geometries into shapes for continuous preforming allows many different types of structures to be produced: I-beams, C-curves or T or H-structures can easily be made via this approach at high production rates (Fauster, Schillfahrt, Hueber, & Schledjewski, 2017).

Figure 12. Example of continuous preforming
Reproduced from the work of Schledjewski, et al.

3.3 Automated placing of VARTM consumables

VARTM processes have seen less automation than RTM processes due to the flexible molds and consumables utilized with a VARTM process. The specifications of the consumables are discussed elsewhere in this review, but there is a litany of variations to the VARTM process, each with specific consumables. This is not to suggest automation is impossible or practiced; an example of an almost fully automated VARTM process was practiced by Premium Aerotec Group. They automated the layup of all vacuum bagging, peel ply, perforated release film, and flow media (Gardiner G. , 2020a). Automation lowered manufacturing costs by 11.5%, operational costs by 31%, overall cycle times by 58%, unrolling of the fabric and the pick-and-place step by 50%, and increased the rate of vacuum bagging by 100% (Gardiner G. , 2020a).

3.4 Economics of automated preforming

Fauster et al. (2017) provided a bottom-up cost model approach comparing different preforming techniques for different preform shapes (Table 6): a T-shaped stringer that is 197 in long, 2 in high, 1 in wide, 0.2 in thick, FVF of 55%, 6 stringers per panel, 6 panels per airplane, and 80 airplanes per year. This adds up to 2,880 stringers produced annually. This analysis showed continuous preforming was the cheapest method for preform production for this process and part (Table 6), but not the lowest mass. Table 6, adapted from the work of Fauster et al. (Fauster, Schillfahrt, Hueber, & Schledjewski, 2017), shows a T-shape stringer cost analysis for several preforming processes. Table 7, also from the work of Schledjewski et al. (Fauster, Schillfahrt, Hueber, & Schledjewski, 2017), shows a weighted decision matrix for manufacturing of T-shaped stringers and highlights the "ease" of manufacturing. This is a somewhat arbitrary rating scale but does highlight some of the important process parameters not included in the bottom-up cost analysis. For the weighted decision matrix, a higher score indicates an easier manufacturing process; therefore, continuous preforming has the lowest cost and easiest manufacturing for a T-shaped stringer under the comparison conditions.

Table 6. T-shape stringer cost analysis for several preforming processes

	AFP direct layup	**AFP selective flat layup**	**Roll forming**	**2D, over braiding**	**Continuous preforming**
Processing parameters					
Number of sub preforms per preform*	2	2	2	1	1
Reinforcement mass per (sub)preform (lbs)	2.03	2.03	2.03	4.06	4.06
Reinforcement material waste (%)	10	5	5	10	5
Total reinforcement mass per (sub)preforms (lbs)	2.23	0.87	2.12	4.45	4.25
Estimated production rate (**) (lbs*hr-1)	11.02	22.05	6.61	11.02	33.07
Total reinforcement mass per (sub)preforms (lbs)	0.4	0.19	0.64	0.4	0.13
Type of reinforcing material	Rovings, binder-based	Rovings, binder-based	NCF, binder-based	Rovings	NCF, binder-based
Raw materials cost ($/lb)	24.68	24.68	32.91	21.94	32.91
Materials cost ($/pc)	109.94	104.94	139.92	97.73	139.92
Facility investment costs ($)	1,210,000	121,000	302,500	847,000	605,000
Deduction period (years)	5	5	5	5	5
Deduction cost per year ($)	242,000	242,000	60,500	169,400	121,000
Deduction costs ($/pc)	84.02	84.02	21.01	58.82	42.01
Operational costs per hour ($/h)	24.20	26.62	12.10	18.15	12.10
Operational costs ($/pc)	19.54	10.26	15.55	7.33	1.55

	AFP direct layup	**AFP selective flat layup**	**Roll forming**	**2D, over braiding**	**Continuous preforming**
Processing parameters					
Working persons	1.5	2	1	1.5	1
Labor costs ($/pc)	87.95	55.97	93.29	43.98	9.33
Total preforming costs ($/pc)	518.92	426.39	518.53	207.85	192.83
Relative preforming costs (%)	269	221	269	108	100
	profile preform is from two L-shape preforms	profile preform is from two L-shape preforms	profile preform is from two L-shape preforms	Over braiding and draping	Direct profile

Table 7. Weighted decision matrix for manufacturing of T-shaped stringers

T-shaped stringer preform		**AFP direct layup**	**AFP selective flat layup**	**Roll forming**	**2D, over braiding**	**Continuous preforming**
Criteria	**Weight**	**Weighted rating**	**Weighted Rating**	**Weighted Rating**	**Weighted Rating**	**Weighted Rating**
Ability to directly realize preform geometry	0.15	0.5	0.2	0.5	0.6	0.8
Flexibility to realize axial profile curvature	0.1	0.5	0.1	0.4	0.4	0.4
Ability to cover fiber orientation along profile transverse directions	0.2	1	1	1	0.6	1
Flexibility in number of	0.1	0.5	0.5	0.5	0.4	0.3

T-shaped stringer preform		**AFP direct layup**	**AFP selective flat layup**	**Roll forming**	**2D, over braiding**	**Continuous preforming**
Criteria	**Weight**	**Weighted rating**	**Weighted Rating**	**Weighted Rating**	**Weighted Rating**	**Weighted Rating**
reinforcement layers						
Ability to realize inline precompaction	0.15	0.8	0.8	0.8	0.5	0.6
Productivity (line speed)	0.15	0.2	0.5	0.6	0.6	0.8
Manufacturing costs	0.15	0.2	0.3	0.2	0.8	0.8
Sum	1.00	3.50	3.25	3.85	3.80	4.55

It is also important to identify that not every part or process is best suited for continuous preforming. Table 8, adapted from the work of Schledjewski et al. (Fauster, Schillfahrt, Hueber, & Schledjewski, 2017), shows the preforming costs and decision matrix scores for C-shaped spar. Performing the same bottom-up cost analysis for a C-shaped spar showed that AFP selective flat layup was the cheapest option for preforming but had the lowest ease of manufacturing score. For this specific use case, the lowest cost option is not the easiest to manufacture.

Table 8. Preforming costs and decision matrix scores for C-shaped spar

	AFP direct layup	**AFP selective flat layup**	**Roll forming**	**Braiding (2D, over braiding)**	**Continuous preforming**
Total preforming costs ($)	22,047.26	16,577.07	28,906.96	31,493.11	19,715.63
Relative preforming costs (%)	133.1	100	174.4	190	118.9
Weighted decision matrix sum	4.40	3.90	4.20	2.90	4.05

4 Non-destructive analysis inspection

Composite imperfections and damage are difficult to determine from the surface alone and include voids, porosity, delamination, fiber breakage, fiber misalignment, matrix cracking, fiber debonding, etc. (Towsyfyan, Biguri, Boardman, & Blumensath, 2020). Figure 13 shows the Eddy current analysis and local fiber volume fraction changes (Bardl, et al., 2016).

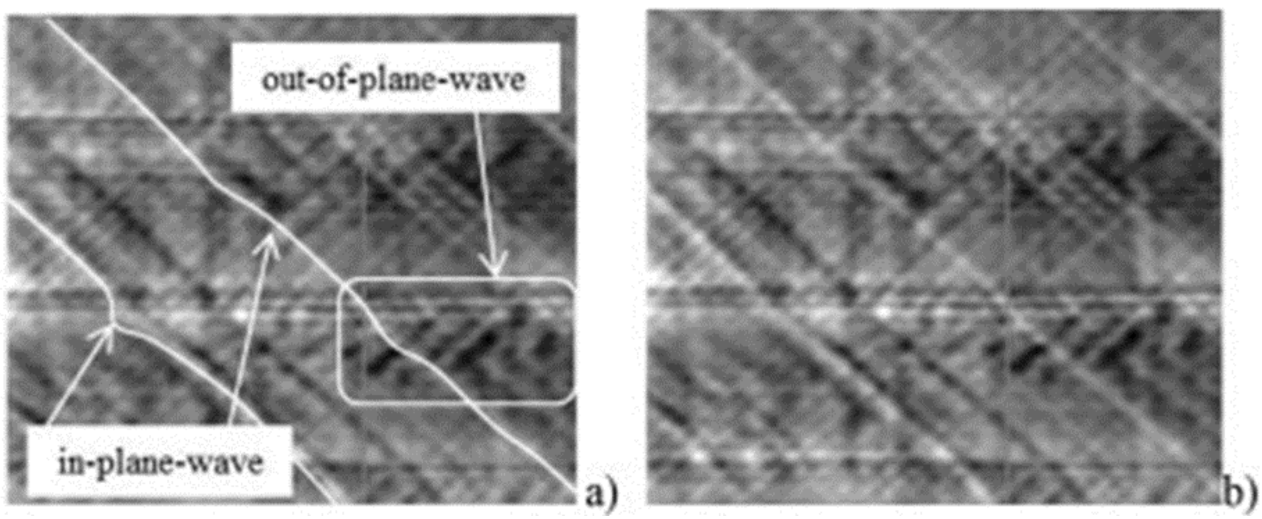

Figure 13. a) Eddy current analysis b) Local fiber volume fraction changes (dark spots)
Reproduced from the work of Bardl et al.

Towsyfan et al. (2020) published a review that identified different types of damage for composites at the coupon level (reproduced in Table 9) and briefly discussed applications and limitations for many different non-destructive inspection/testing (NDI/NDT) methods. Towsyfyan et al. (2020) also developed an easy-to-understand quick reference guide for applications and limitations (reproduced in Table 10). A higher score indicates the better capability of each technique to detect the identified damage.

Table 9. Different types of composite damage

Damage	**Overview**
Void and porosity	Voids can occur during manufacturing. Porosity can be caused by poor curing, volatiles, cavitation, or incomplete infusion.
	Porosity can cause 7 % decrease in inter-laminar shear for every 1 % porosity.
Delamination	Caused during manufacturing or impact and delamination resistance is generally low for composites.
	Delamination can reduce compressive strength and stiffness.
Fiber breakage	Fibers exhibit brittle failure and can increase crack length at fiber-matrix interface.
Fiber misalignment	Misalignment changes mechanical properties i.e., tensile and fatigue performance. 10° misalignment can lower compressive strength by 30 %.
Matrix cracking	Matrix cracking is the initial mode of failure for composites and can lead to delamination. It can also cause fiber breakage due to stress concentration.
Fiber debonding	Separation of matrix and fiber.

Table 10. Scoring matrix for NDT methods to measure composite failure

	Porosity	**Delamination (<10 mm)**	**Delamination (>10 mm)**	**Fiber Breakage**	**Fiber Misalignment**	**Matrix Cracking**
UT C-scan	9	9	10	0	9	0
Acoustic Emission	0	7	7	10	0	10
Transient Infrared Thermography	6	8	10	0	2	0
Laser Shearography	8	9	10	6	2	0
X-ray	10	7	7	5	5	6

The MSU market engagement uncovered the market desires high-quality inspections of the dry fabric preforms before infusion and is worried about ensuring correct fiber direction after infusion. A commercially available prepreg will arrive with a certificate of analysis that tightly defines and controls many parameters, such as resin content, fiber direction, etc. Performing resin infusion removes this control during purchasing and moves the quality measurement onus to the part producers themselves. Figure 14 shows an example of the Eddy current to detect plies at different thicknesses (Bardl, et al., 2016).

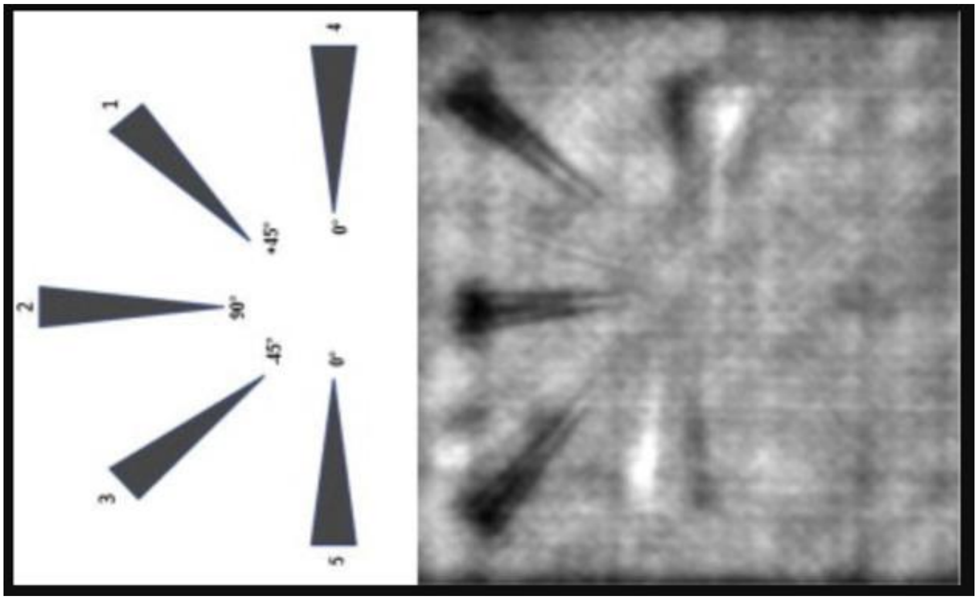

Figure 14. Example of Eddy current to detect plies at different thicknesses
Reproduced from the work of Bardl et al.

One method to address this limitation is to automate measurements of local fiber volume fraction and fiber direction for the dry preforms via Eddy currents. Fiber misalignment, even a moderate misalignment of 10°, can decrease the compression strength by 30% (Bardl, et al., 2016). Most methods focus on the surface of the dry preform, but measuring via Eddy currents can allow for deeper penetration, at least up to 5 layers thick (Figure 17). The 3D preforms can also be measured by using a 6-axis robot where the fiber direction can be observed (Heuer, et al., 2015). Eddy currents can be used to detect fiber waviness and local fiber volume fractions as seen in Figure 15 (Bardl, et al., 2016).

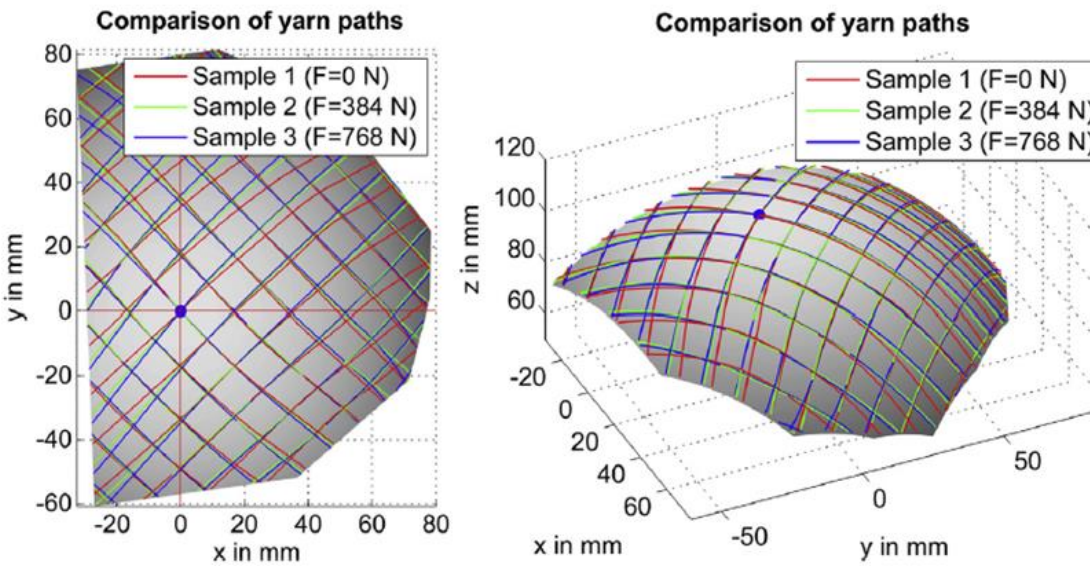

Figure 15. Measuring fiber direction by Eddy currents for 3D dry fabric preform
Reproduced from the work of Bardl et al.

The above shows the capability of new technology to address the current limitations for resin infusion: quality assurance of the dry fabric preforms and of the final assembled part subsurface layers prior to infusion. The NDI process for a cured resin-infused composite part is no different than for a prepreg composite part.

5 Simulation

Simulation is also a challenge for composites, but simulation is such a broad topic and cannot be faithfully covered in this review. Prepreg materials have a long history and the legwork of developing the many material models through copious testing has been completed. Resin infusion does not have this privilege and will require substantial material testing to become competitive to prepreg simulation. Additionally, resin infusion can have many more iterations of the material system than prepreg materials, requiring focused material model development.

Briefly, one item lacking for resin infusion is an accurate method for predicting the drapability of the dry fabric preform. It is important to prevent wrinkles and damage, reduce waste, and control the fiber direction (Vita, Castorani, & Germani, 2018). The dry fabric drapability will affect permeability, fiber volume fraction, nesting, etc. Sliding of the dry fabric layers can cause defects in the preform and modeling has attempted to address all the issues thus described (González, Vilatela, Molina-Aldareguia, Lopes, & LLorca, 2017). Figure 16 is a model of the drapability of a preform (Bardl, et al., 2016).

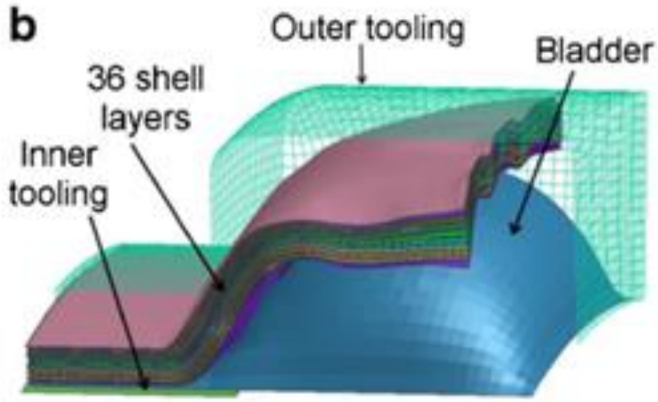

Figure 16. Model of drapability of a preform
Reproduced from the work of Bardl et al.

Also, to predict the final mechanical properties, it is important to understand how the infusion process will affect the preform. This is challenging because the resin infusion process needs to be modeled at several different levels: microscopic – resin flow within individual tows; mesoscale – the resin infusion process for the part; macroscopic – the mechanical performance of the part, just to name a few items (González, Vilatela, Molina-Aldareguia, Lopes, & LLorca, 2017).

Many parts need to be simulated well for composites in general: brittle fracture in-plane, fiber kinking in-plane, matrix and fiber interface failure, out-of-plane tension, plastic deformation of the resin, in- and out-of-plane compression, and fiber and resin interlaminar shear. These challenges are the same for prepreg and infused systems, although resin infusion affords more opportunity for mixing and matching of reinforcements and matrices -- a strength for resin infusion but this breadth of variations also introduces more material testing to produce accurate simulation (González, Vilatela, Molina-Aldareguia, Lopes, & LLorca, 2017). An example of incorporating multiple scales and failure mechanisms is found in Figure 17 (Lopes, Sadaba, Gonzalez, Llorca, & Camanho, 2016).

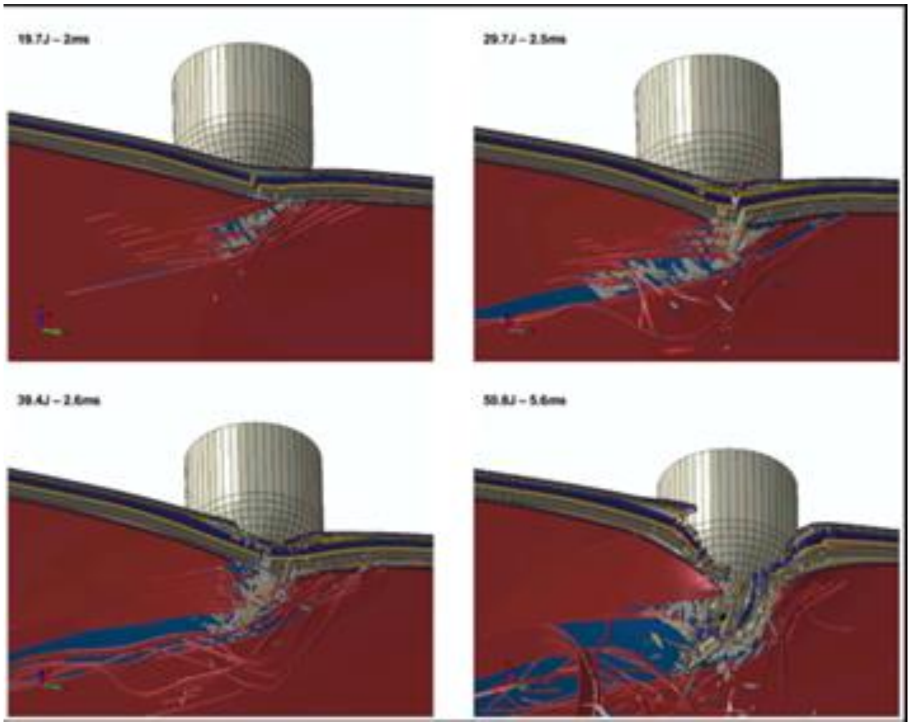

Figure 17. Example ballistic impact for a composite laminate
Reproduced from the work of Llorca et al.

5.1 Sensitivity analysis for composites

A paper published by NASA showed a sensitivity parameter to identify at which angles each physical parameter is most affected (Hafiychuk, 2016). Figure 18(b) (Bednarcyk, Aboudi, & Arnold, 2014) shows an α value, the angle around a circle, with 0 being in line with unidirectional fiber. Progression around the circle shows how different physical parameters are more or less important at certain angles. This work can help industry to better understand what physical parameters matter more for each intended application and what needs to be monitored more closely based on these applications. An intuitive data point is the significant loss in tensile properties (black line in Figure 18(b) with small changes in angle (Gardiner G. , 2019a).

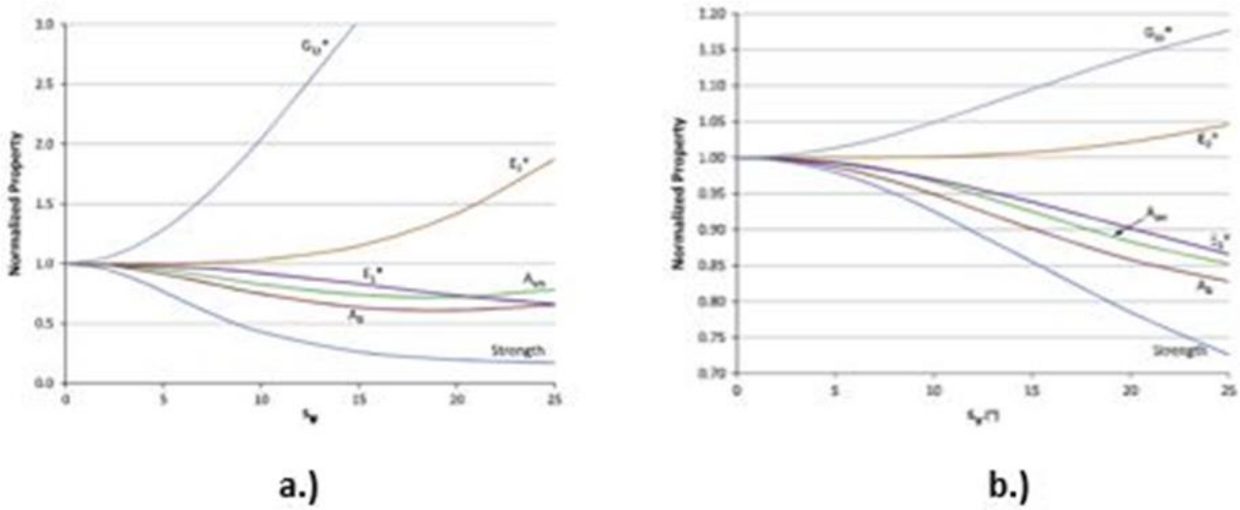

Figure 18. How fiber direction deviations can affect final properties

Reproduced from the work of Hafiychuk et al.

6 3D Printing tooling for molding

Tooling is an important limitation for infusion process in general, more so for RTM processes. Polymeric additive manufacturing, more commonly called 3D printing, has begun to demonstrate the ability for tooling for both VARTM and RTM.

Through a partnership with Purdue University, Thermwood has made a 3D-printed tool for compression molding of thermoset parts. Using the Thermwood LSAM, a thrust reverser blocker door of 10 in x 13 in x 2 in part was made with a 50% fiber volume fraction. The mold was produced in two parts and took less than 3 hours to print with an additional 27 hours of machining. Placing metal supports on the outside of the mold allowed 1,500 psi in compression during initial testing (Marrett, 2019).

Cincinnati Inc., Sabic, and the University of Dayton developed a 3D-printed tool that can withstand AC conditions (350 °F, 80-90 psi). They measured the dimensional stability for the part after 20 AC cycles and found most of the tool deflected less than 0.004 inches (Thompson, Huelskamp, Allessio, & Ly, 2019).

A commercial example of a 3D-printed tool was for the Dassault Falcon Jet using a Stratasys ULTEM 1010 material. The part was designed to handle vacuum at 250 °F. A cost and lead time analysis showed the ULTEM material could lower costs and lead time by ~ 5x: the FRP tool cost $25,000 and took 16 weeks to produce, the ULTEM part cost $5,600, and it took one to three weeks to produce (Stratasys, n.d.).

Magnum Venus Products have the world's first 3-D printer capable of printing vinyl ester and epoxy thermosets, partnering with resin producer Polynt. This novel technology will allow the advantages of 3D printing, such as rapid prototyping, flexibility in structure, and higher material utilization, but thermoset printing will also allow for extremely high performance and options not currently possible with traditional thermoplastic additive manufacturing (Gardiner G. , 2019a). This reactive additive manufacturing system will allow for longer open layer times and various filler media to be inserted (foams, sensors, threaded inserts, reinforcement). Additionally, this system requires no additional heating during printing, but does require a post-cure to reach maximum mechanical performance. As a post-cured, thermoset material, the coefficient of thermal expansion is more isotropic for reactive materials when compared to thermoplastic printed materials, and the thermal expansion is very low, ~ 3-8 ppm in the X-direction, depending upon formulation.

The advantages of thermoset printing will be initially for research and development tooling. The printed tool can have the surface machined away and then a new surface can be reprinted, allowing for changes to the tool surface without requiring a completely new tool. A further advantage is the current Polynt vinyl ester system has performance similar to the extreme engineering thermoplastics, i.e. PEI, PEKK, PEEK, and PESU, but with a much lower price. Additionally, there is almost no limit to the size of the tooling as each 8 ft x 4 ft x 4 ft section could be post-cured together, to essentially produce a single, large tool. Therefore, R&D tooling can be produced for aerospace parts rapidly, economically, reusable, and large-scale.

An example tool produced at Mississippi State University shows a 6 ft x 4 ft x 6 in closed mold generic spoiler closed mold tool was designed, printed, machined, and coated within 3 weeks and cost less than $10,000. This is an extremely rapid turnaround for tooling suitable for RTM closed mold processes as an invar tool was quoted to take 12-18 months and cost over $60,000.

7 Disadvantages during resin infusion manufacturing

There have been four main disadvantages identified in the literature for various RTM processes. The first is related to the dry fabric preform: deformation of the fiber during placement or of the preform during manufacturing (Konstantopoulos, Hueber, Antoniadis, Summerscales, & Schledjewski, 2019). This can cause changes in the permeability of the system, which can cause resin pockets or voids. Further, the dual-scale porosity due to the difference in permeability between in-plane and out-of-plane can also cause voids to form (Bednarcyk, Aboudi, & Arnold, 2014). More extreme issues with fiber deformation, such as missing tows, gaps, or cuts of the fabric, can cause race tracking (faster flow of a resin due to low flow resistance) of the resin

(Niggemann, Song, Gillespie, & Heider, 2008). An example of this, discussed in this report section entitled “What is Microcracking”, is the small resin-rich regions formed due to the non-structural stitching (warp stitching) of non-crimp fabrics (NCF). The preform can also have issues with fiber deformation because the fabric is “slippery” and can slip during manufacturing, causing poor and/or non-repeatable mechanical properties. The pressure from the vacuum bag can also move the tows, causing all the above issues and can create different amounts of nesting, affecting permeability (Li, et al., 2018). Some resin infusion processes, such as HP-RTM, can have other issues like fiber wash out due to the high pressure at the resin inlet (Aranda, Berg, Dickert, Drechsel, & Ziegmann, 2014).

Another issue for resin infusion is the chemical composition of the matrix. Having the composite part producer mix a two-part resin system allows for issues with ratios of the two parts and/or local concentration fluctuations. Poor mixing can cause several different issues such as a change in mechanical properties due to the unpredictable molecular weight of the final system or excessive exothermic reactions due to local hardener concentrations.

A third issue, but related to the second, is variation in the cure temperature. Out-of-autoclave (OoA) processes can have thermal inconsistencies when using a room-temperature cure compared to AC or oven curing. In particular, there can be difficulty controlling the rate of change of temperature during heating from one side of the laminate/tool interface to the other. Large RTM cells can have issues when curing multiple parts (Konstantopoulos, Hueber, Antoniadis, Summerscales, & Schledjewski, 2019).

A fourth identified issue is the part-tool interface. Any locations where the preform has poor surface interaction, either through the quality of the preform, placement, or deformations in the reinforcement can cause issues with the infusion. There can also be edge effects on the tool that can cause race tracking of the resin: the difference in permeability can be up to 30x. These edge effects can be exaggerated if the tool has any deflection due to injection pressure or compaction pressure (Lawrence, Barr, Karmakar, & Advani, 2004). Tool deflection can also cause uneven thickness in the final part, leading to a knockdown in stiffness. Although higher-pressure resin infusion processes such as RTM may have more issues of tool deflection, VARTM processes are not immune to this issue due to the soft bagging tool side (Konstantopoulos, Hueber, Antoniadis, Summerscales, & Schledjewski, 2019).

8 List of notable projects working on resin infusion

Below is a list of notable projects that have made significant progress in novel technologies, including resin infusion. A few historical projects are highlighted as stitched resin infusion was heavily researched in the 1990s and early 2000s. The interest in OoA processes has intensified recently with efforts to increase commercial aerospace manufacturing rates; therefore, current projects are highlighted that are investigating resin infusion, along with other technologies.

8.1 Tailorable feedstock and forming (TFF)

Tailorable universal feedstock for forming (TuFF) is a highly aligned, discontinuous fiber system developed by the University of Delaware. Tailorable feedstock and forming (TFF) is meant for composites that weigh less than 20 pounds. The main reason for the TFF program was to develop a material that can demonstrate metal-like formability and be tailored to meet a range of DoD application volumes and needs. The two main objectives for TFF are to provide a material with a low price that can be formed into complex shapes. The TuFF concept orients short carbon fibers with small diameters to allow the greatest improvement in structural properties, achieving greater than 95% fiber alignment within 5 degrees of the desired direction (Gardiner G. , 2020c). TuFF feedstock can give the same fiber volume as unidirectional prepregs and composite laminates can be produced with less than 1% voids. Publicly available properties for the TuFF feedstock are shown in Figure 19 (Gardiner G. , 2020c).

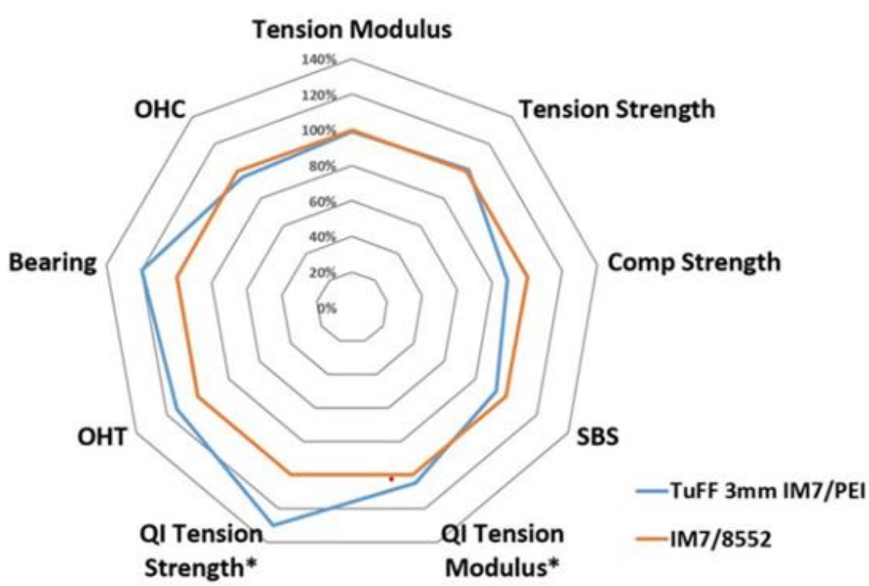

Figure 19. TuFF Feedstock compared to UD prepreg properties

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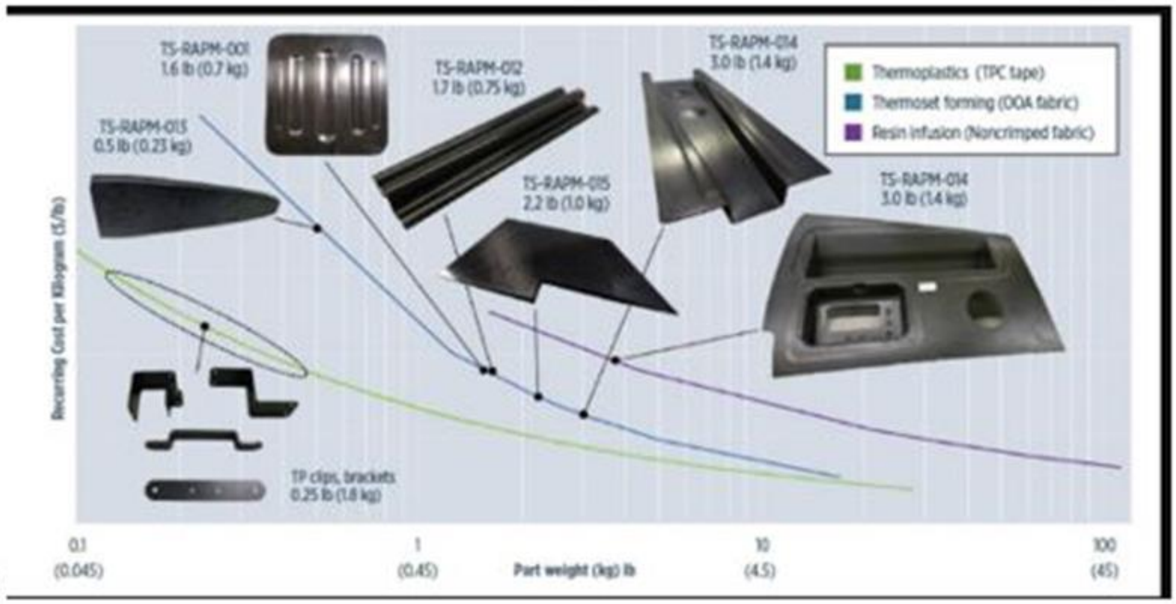
8.2 Rapid high-performance manufacturing (RAPM)

The goal of rapid high-performance manufacturing (RAPM) was to "revolutionize the cost paradigm for small composite parts, enabling pervasive use in defense applications" (Gardiner G. , 2020d) with a performance goal of 30 minutes on tool and post-cure of 60 minutes at 356 °F.

There are three primary tracks for the RAPM project: resin infusion, thermoset prepreg, and thermoplastic forming. The forming trials were split into a manufacturing development phase followed by the challenge/transition phase. The manufacturing development phase used three primary part configurations of beaded-panels, a rib, and a curved C-channel. The beaded panel had out-of-plane features with pad-ups, pad-downs, and a vertical edge; the curved C-channel had variable radii, variable flange curvature, and web ply drops; the rib panel had an edge joggle and a pad-up with multiple 90-degree edges. Figure 20 shows the various manufacturing processes and when they provide the most economical recurring costs, which heavily depend on part complexity and weight (Gardiner G. , 2020d). The large-scale resin-infused structure showed the best economics for the heaviest-weight panels. For the resin infusion test article shown in Figure 20 the deep-draw radii showed delamination issues, likely because of insufficient initial cure before demolding. Early trials had an unexpected problem in the flow near the exit, causing fiber distortion. The inlets and outlets were reversed to rectify the issue. The finished parts showed full consolidation, excellent fiber alignment, and passed production requirements for nondestructive testing. Part layup piece count was reduced by more than 66% compared to prepregs and touch labor dropped by 90%.

It is also important to highlight resin infusion was shown to be more economical than aluminum for the specific part tested, see Figure 20(b).



A)

	Resin Infusion RI-RAPM-004 Deep Draw	Thermoset Prepreg TS-RAPM-012 Wave	Thermoplastic Forming TP-RAPM-013 Rib
Parts per Shipset	5	4	18
Weight Savings per Shipset	5.6 kg	1.8 kg*	3.5 kg
Recurring Cost Savings	67%	-7%	12%
Potential Savings over Life of Program	≈ $3,000,000	NA	≈ $900,000

FIG. 6 Comparing cost vs. aluminum

RAPM calculated recurring manufacturing costs (e.g., materials, machine time) for selected challenge and transition parts, assuming non-recurring infrastructure was in place, and then compared these to machined aluminum.

*Opportunity exists to reduce weight an additional 0.5 kg via a more tailored preform.

Fig. 6. Comparing cost vs. aluminum

RAPM calculated recurring manufacturing costs (e.g., materials, machine time) for selected challenge and transition parts, assuming non-recurring infrastructure was in place, and then compared these to machined aluminum.

B)

Figure 20. Various manufacturing processes with most economical recurring costs

A) Plots from Boeing RAPM project comparing thermoplastic, aluminum, and VARTM processes for different parts. B) Cost difference for Resin Infusion, Thermoset prepreg, and Thermoplastic forming vs aluminum

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8.3 Wing of Tomorrow

One of the goals of the Wing of Tomorrow project is to develop a high-rate commercial aircraft wing structure manufacturing process that is an order of magnitude better than current wing manufacturing technology. Wing of Tomorrow is a conglomerate of academic and industrial partnerships, started in 2015. The main focal areas assessed for improved manufacturing technology include automation, fewer parts/part integration, faster cycle time, faster assembly, and faster NDI (CompositesWorld, 2019a). The National Composite Centre is expanding its facilities for the Wing of Tomorrow project and adding ten new pieces of equipment, including dry fiber placement machines from Electoimpact, molds, and metering systems to assist in manufacturing composite wing structures at a much higher rate.

The most daunting challenge for composite manufacturing is the rate of production. Airbus currently manufactures ten composite-intensive A350s per month. If the composites were to be used for the A320, there would need to be roughly 100 shipsets per month for future targeted rates. Prepreg composites could meet this demand but would require a substantial increase in manufacturing footprint, freezers, autoclaves, etc.

The Wing of Tomorrow project will assess the cost and the rate viability of OoA processes for the manufacturing of wing structures, including wing skin/stringers, spars, and ribs. With support from both research centers and commercial partners, the project has shown that manufacturing complex aircraft components more efficiently and cost-effectively is attainable.

8.4 Clean Sky 2

Clean Sky 2 is a project to reduce the environmental impact of air travel. One project was to produce a fully composite wing box. MTorres demonstrated a fully composite dry fiber wing box for the C-295 aircraft, using a stiffened lower wing skin that included integrated forward and rear spars (Gardiner G. , 2021b). The MTorres team developed a combined infusion process that uses a single resin inlet but three variations of infusion: the Airbus VAP process, use of distribution media, and areas that required hard cauls on both sides (Gardiner G. , 2021a; Gardiner G. , 2021c). Particular attention was paid to the integration of the soft tooling process to maintain tolerances along the edges and corners of the wing box. (Gardiner G. , 2021c)

8.5 Comdor

Latécoère developed an aircraft door demonstrator that would fit the Boeing 787 or Airbus A350 XWB. The part was produced from 45 different sub preforms that are stitched together through-the-thickness. Latécoère Combined the though-the-thickness stitching with RTM to produce the door using Hexcel HexForce G0962 carbon fiber fabric (370 g/m^2) and RTM6 epoxy (CompositesWorld, 2012). The placing of the dry fabric "sub-preforms" was very difficult and is proprietary. The sub-preforms were cut with an ultrasonic cutter to prevent fraying/thread pullout and to provide very accurate dimensions as the sub preforms were 2D and laid into a 3D mold (Gardiner G. , 2013). Using through-the-thickness stitching allowed the door to remove ~ 800 titanium fasteners normally used in a door.

8.6 Airbus A350 door with HP-RTM

In 2019, Ginger Gardiner wrote an article in Composites World to discuss the evolution of the door for the Airbus A350 (Gardiner G. , 2019b). In the TAKE OFF program sponsored by the Austrian government from 2013 to 2015, Airbus used HP-RTM technology to manufacture Airbus A350 assembly doors. Initially, the aircraft door used conventional RTM technology, consisting of 14 parts. Due to the number of parts, multiple debulking steps were needed, resulting in a three-day production cycle. Moreover, conventional RTM requires multi-piece tools in the production process. In 2018, Airbus began to use the new HP-RTM process to manufacture next-generation doors, in only 4 hours, using one upper and one lower mold, and making the door in a single piece.

8.7 Boeing/NASA hybrid wing body

The main goal of any new aircraft system is a lighter, cheaper system that can produce higher lift-to-drag ratios, reduce drag, and lower community noise. The Hybrid Wing Body (HWB) offers improvement in aerodynamic performance compared to traditional aircraft structures (Jegley, Przekop, Lovejoy, Rouse, & Wu, 2020). Although there are many advantages to the hybrid wing body shape, there are also a couple of challenges that come with it. First, the fuselage presents problems because the hybrid wing body does not have a circular cross-section; current composite structures could not support the cost, weight, and performance demands that these novel aircrafts require. Specifically, secondary stresses develop in this cabin and a traditional composite material would require too many mechanical attachments and fasteners for damage arrestment. Second, with each individual part needing its own toolset, the cost of the HWB concept would be too expensive with traditional composite structures.

Figure 21, shows the loading configuration of a Hybrid Wing Body concept (Jegley, Przekop, Lovejoy, Rouse, & Wu, 2020). Figure 23, shows the path leading to Hybrid Wing Body large test article (Mukhopadhyay, 2014). Unlike traditional cylindrical fuselages, the Hybrid Wing Body concept has a bi-axial loading pattern that will occur during maneuver loading conditions and provide equal load magnitudes in each in-plane direction. This suggests that the optimum panel geometry should have continuous load paths in both directions, unlike the traditional, circular airframes that have most of their load in the N_x direction.

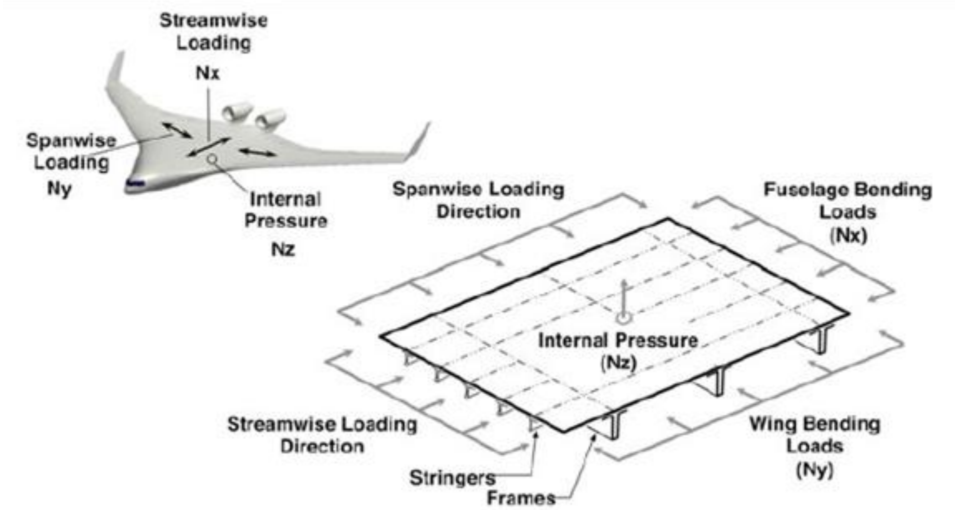


Figure 21. Combined loading on HWB pressure cabins
Reproduced with permission from CompositesWorld

The Pultruded Rod Stitched Efficient Unitized Structure (PRSEUS) was developed by NASA and Boeing as a solution to provide a lighter, more robust airframe (Mukhopadhyay, 2014). It is a combination of dry carbon warp-knit fabric, pultruded rods, foam core, and stitching threads that can be produced in a one-piece panel with seamless transitions and damage-arrest interfaces. The pultruded rod will improve bending stiffness and move the stiffening away from the skin surface.

Figure 22 shows how the PRSEUS panel concept is constructed (Mukhopadhyay, 2014). The rod stringer is passed through a small keyhole in the frame web, which allows for load path continuity at the stringer-frame intersection in both directions. The stitches suppress the out-of-plane failure modes and allows a higher degree of tailoring compared to a traditional laminate. The PRSEUS panel is highly efficient in all three loading directions, reacts well to pull-off loading, and increases panel survivability.

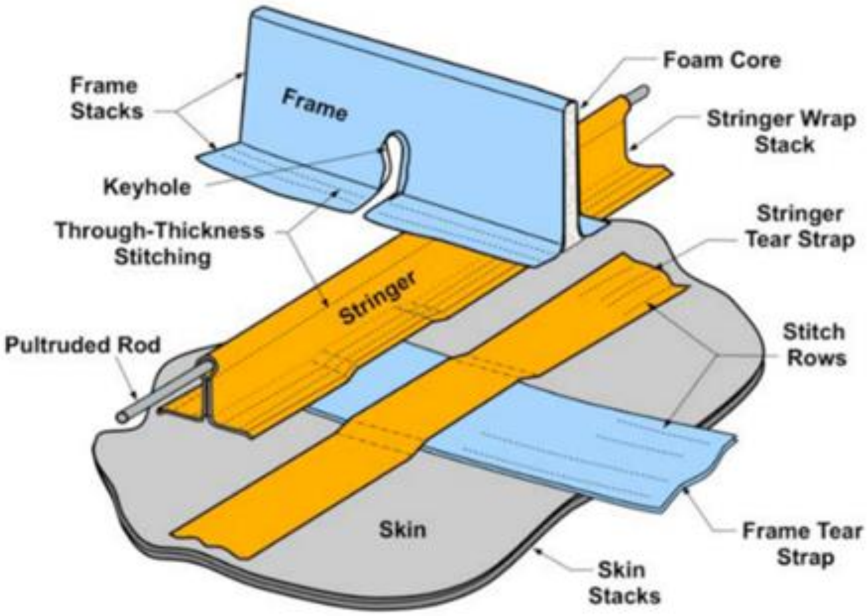


Figure 22. Exploded view of PRSEUS Concept

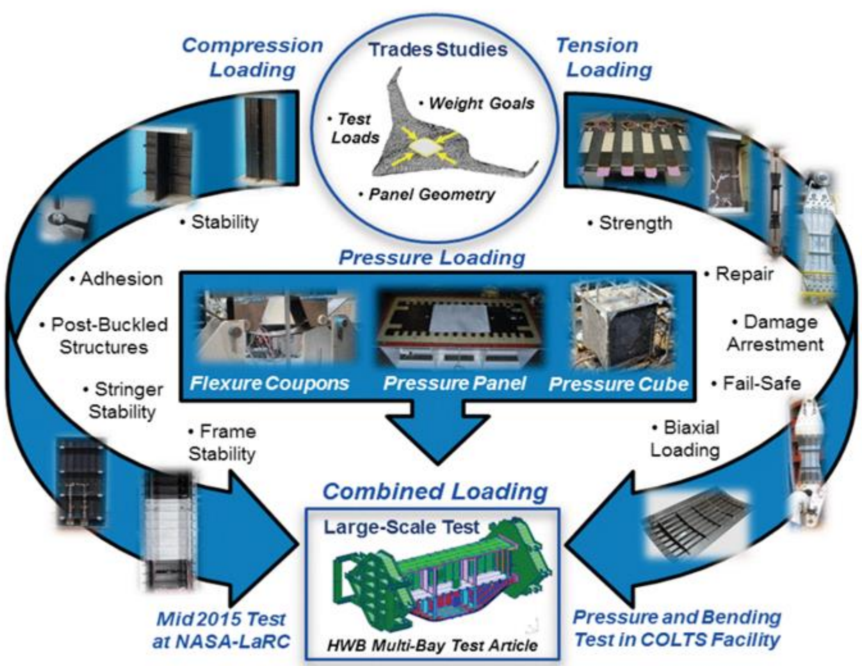


Figure 23. Path leading to hybrid wing body large test article

Reproduced from the work of Jegley et al.

Figure 24 is an example of how the addition of stitching can prevent the crack tip from propagating (Mukhopadhyay, 2014). As an example from the PRSEUS panel, a slot was cut in the center stringer and then loaded in tension -- the panel could continue carrying a load up to 132% of design limit load, with a non-catastrophic failure. The distribution of the load and the turning of the crack could stop the damage from propagating beyond the stitch rows until the undamaged bays failed.

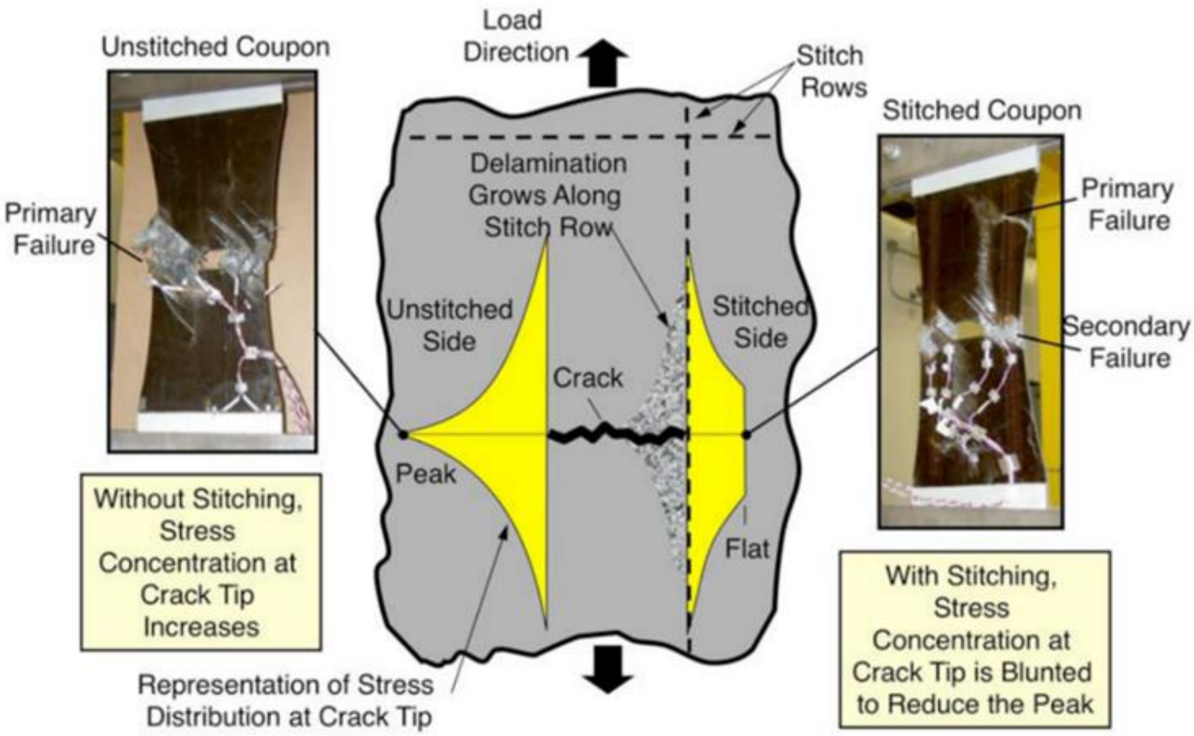


Figure 24. Blunting stress concentration at the crack tip from stitching
Reproduced from the work of Jegley et al.

Figure 25(a), is the overall axial displacement with key damage event load levels. This shows that the global structural behavior was unaffected by propagation damage until it progressed beyond the two-bay region and that crack turning relives crack tip stresses Figure 25(b). The PRSEUS Panel concept had met the primary structure design requirements and even surpassed the Hybrid Wing Body weight goals, proving the Hybrid Wing Body could be achievable using the PRSEUS structure.

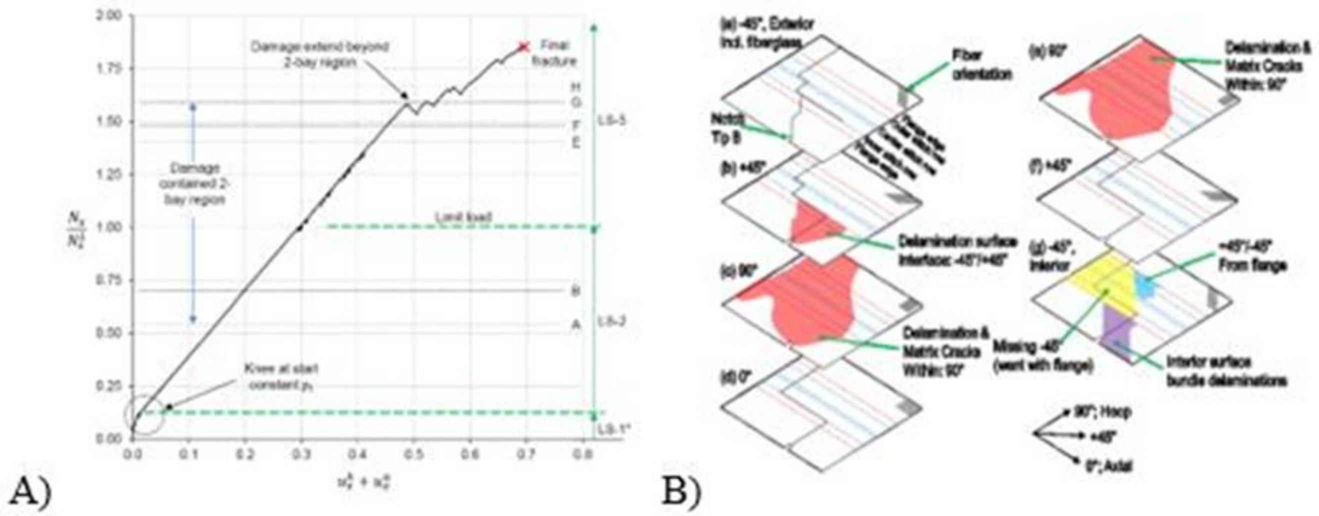


Figure 25. A) PRSEUS panel load vs displacement B) Schematic of failure extent
Reproduced from the work of Velicki et al.

8.7.1 PRSEUS strength and performance

Table 11, Table 12, and Table 13, all reproduced from Johnston et al. (2013), highlight the mechanical performance of the PRSEUS structure. The material used to test the panel is an AS4 fiber with a VRM-34 epoxy resin, both from the Hexcel Corporation. Coupons, both stitched and unstitched, with all varying thicknesses were tested at 72 °F and 180 °F, the stitching thread was 1600 Vectran thread at 5.08 stitches per inch. There are two stitch types incorporated into the PRESUS panel: the first stitch is placed near the center of the skin near the stiffener element lower flange half and is oriented normally to the skin surface. The second stitch is inclined on the bag side of the panel with the stiffener web and then exits on the tool side under the stiffener web. Each specimen set contains six replicates.

Table 11. Testing matrix for the PRSEUS panel

Test Type (ASTM test)	**Test Temperature °F**	**Unstitched**	**Stitched**	**Specimen Dimensions, in.**	**Extensometer/ Strain Gages**
Tension (D3039)	72, 180	Y	Y	12 x 1 x .063	Back-to-back / back-to back at 90°
Compression (D6418)	72, 180	N	Y	6 x 0.5 x .157	None / back-to-back axial
In plane Shear (D7078)	72, 180	Y	Y	2.2 x 3 x .157	None / back-to-back at ±45°
Mode I Fracture Toughness (D5229)	72, 180	Y	N	7 x 1 x .314	None
Mode II Fracture Toughness	72, 180	Y	Y	7 x 1 x .314	None

The presence of stitching had minimal effect on the shear properties at ambient temperatures. At elevated temperatures, the presence of stitching greatly reduced the shear properties (Table 12). Mode I fracture toughness could not be assessed for stitching because of the unsteady crack growth, presumably due to crack arrestment due to stitching. The presence of stitching greatly increases the Mode II fracture toughness but increases variability (Table 13).

Table 12. Percent change in shear properties of stitched and unstitched specimens at 72 °F

Property	**Test Temperature**	**Stitching**		
		Unstitched	**Stitched around Notch**	**Stitched through Notch**
Shear Modulus	72 °F	-	5.9%	0.8%
	180 °F	1.3%	-13.2%	-17.4%
Ultimate Shear Strength	72 °F	-	2.8%	-5.5%
	180 °F	-3.2%	-16.6%	-23.2%
5% Offset Shear Strength	72 °F	-	-5.5%	-2.2%
	180 °F	0.3%	-23.2%	-21.1%

Table 13. Mode II fracture toughness of unstitched and stitched laminates

	Test Temperature °F	Specimen	Specimen GII in-lbf/in2		Average GII (SD/COV) in-lbf/in2	
			Non-Precracked	Precracked	Non-Precracked	Precracked
Unstitched	72	1	1.96	1.53	2.11 (0.37/ 17.5%)	1.63 (0.110/ 6.75%)
		2	2.30	1.69		
		3	2.22	1.46		
		4	1.99	1.74		
		5	1.55	1.69		
		6	2.66	1.69		
	180	1	2.01	1.57	2.03 (0.100/ 4.93%)	1.69 (0.130/ 7.69%)
		2	2.07	-		
		3	2.06	1.87		
		4	1.97	1.59		
		5	2.18	1.77		
		6	1.89	1.62		
Stitched	72	1	3.06	3.85	2.49 (0.550/ 22.1%)	3.02 (0.710/ 23.5%)
		2	2.61	2.51		
		3	2.37	2.05		
		4	1.63	3.46		
		5	3.07	2.66		
		6	2.24	3.58		
	180	1	2.85	2.91	2.97 (0.419/ 14.1%)	3.66 (0.739/ 20.2%)
		2	2.91	2.80		
		3	-	-		
		4	3.19	4.30		
		5	3.51	4.29		
		6	2.38	3.98		

8.8 Advanced Composites Technology (ACT) program

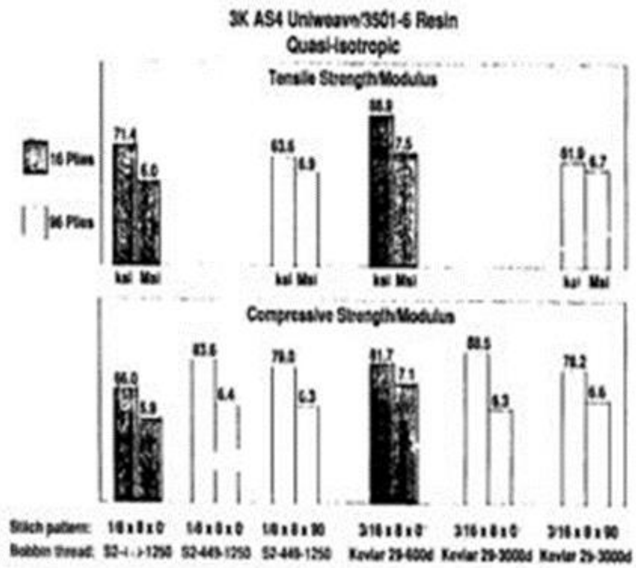
The NASA Advanced Composites Technology (ACT) program was established in 1988 with the goal to improve composite efficiency and lower manufacturing costs (NASA, n.d.).This project dealt with stitching reinforcement combined with resin transfer molding for transport wings and fuselages. The thread materials were Kevlar and glass thread and new stitching techniques were adopted to speed up the stitching process. Thin and thick ply stitched laminates were infused and tested to determine the strength properties (Davis Jr. & Bohon, 1992).

Figure 26(a) highlights the difference in tensile and compression properties between the glass and Kevlar stitched samples. The Kevlar stitched samples showed higher in-plane mechanical properties than the glass stitched samples. The compression after impact (Figure 26(b)) can be increased by using a hybrid Kevlar and glass stitch. Overall, stitching requires thoughtful consideration between in-plane knockdowns and out-of-plane improvements. Novel threads, such as Vectran, are now used in place of legacy Kevlar due to the propensity of Kevlar to absorb moisture (Davis Jr. & Bohon, 1992).

NASA's ACT Program also explored many other facets of stitched composites such as failure modes, different stitch composite parameters, microcracking, the effect of humidity, the ply orientation, and improving existing materials. It was concluded that stitching can have multiple improvements on laminates by providing damage tolerance, acceptable fatigue behavior, and acceptable hot/wet performance (Davis Jr. & Bohon, 1992).

The ACT program also showed stitched resin-infused (SRI) parts may save substantial amounts of weight compared to an aluminum wing box. An SRI wing box, with pad-ups for environmental effects weighed 4,184 lbs. while an aluminum wing box weighted 5,942 lbs, a savings of 29.6 %. Also, the SRI wing box can have a higher aspect ratio, 12.1 vs. 8.5 compared to the aluminum wing box. The study did not compare a prepreg wing and an SRI wing (Karal, 2001).

A.)



B.)

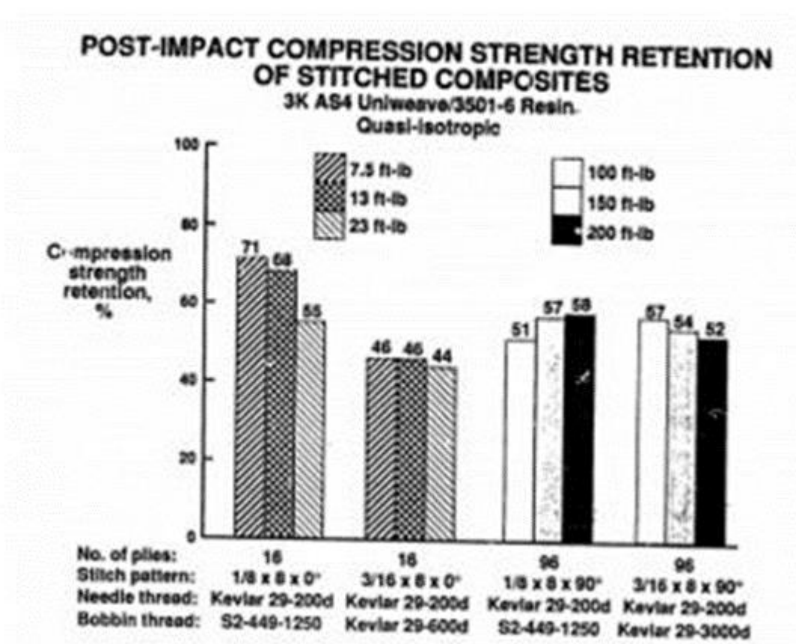


Figure 26. A) Tensile and compression strength of stitched laminates B) Compression strength retention of stitched composites

Reproduced from Bohon et al.

Every technology has difficulties that prevent adoption, which for this technology were: thread choice causing more hygrothermal microcracking, processing difficulties that required resin film infusion, and “slow” stitching as the entire surface was stitched. Progress in technology can address all of these issues such as using novel thread material, novel resins with lower viscosity appropriate for infusion, and strategic stitching only where required.

9 Resin infused in production and development

9.1 Resin infused parts by OEM

The following section begins with two tables showing flying examples of resin-infused parts for commercial transport. Specific aircraft are highlighted such as the Boeing 787, multiple Airbus examples, and the Russian Irkut. Later, specific parts are discussed where more public information was available about the application, material, and processing.

A collection of aircraft parts using resin infusion has been compiled and tabulated for Boeing in

Table 14 and in Table 15 for Airbus, Irkut, and Comac. The tables show Airbus leans towards RTM processes over VARTM processes while Boeing, on the other hand, prefers VARTM processes. After the production ceases of the Airbus A380, there will be no active commercial aircraft that employs a stitched resin-infused part. It is important to highlight the Airbus A220 and OEM Irkut MC-21 aircraft as they are significant steps forward for resin infusion.

Table 14. Examples of primary structures from Boeing using resin infusion

Manufacturer	**Aircraft**	**Aircraft type**	**Part**	**Process**	**Fiber**	**Resin**
Boeing	C-17	Military	Landing gear door	Stitched infusion CAPRI VARTM		
			Forward fuselage fairings	Stitched CAPRI VARTM		
Boeing	787	Wide body	Aileron, flaperon, inboard and outboard flaps	CAPRI VARTM	HexForce 12k spread tow carbon fiber	HexFlow RTM6

Manufacturer	Aircraft	Aircraft type	Part	Process	Fiber	Resin
			Rear pressure bulkhead	VARTM		Solvay PRIFORM
			Landing gear braces	RTM		
			Rudder shell			
			Horizontal stabilizer			
Boeing	747		Bullnose	VARTM		
Boeing	757		Door			
			Landing gear braces			
Boeing	777		Horizontal stabilizer rib			
Boeing	777x		Exhaust frame			
			Fan case (GE)			

Table 15. Airbus, OEM Irkut, and Comac primary structures using resin infusion

Manufacturer	Aircraft	Aircraft type	Part	Process	Fiber	Resin
Airbus	A400M	Military	upper cargo door	VAP		HexFlow RTM6
Airbus	A380	Wide body	Rear pressure bulkhead	RFI/VAP Stitched		
			Door hinge arm	RTM	HexForce G0926	HexFlow RTM6
			Aileron spar			HexFlow RTM6
			Radome	RFI		
			wing box			

Manufacturer	Aircraft	Aircraft type	Part	Process	Fiber	Resin
			flap track panels			
			actuator brackets	RTM		
			rudder support structure	RTM		
			wing trailing edge panels	RFI		
			Hinge fitting			
			fan cowls	RFI		
			rear fan			
			center fan			
Airbus	A330		spoiler fitting	RTM		Cytec 977-20 epoxy
Airbus	A340	Wide body	spoiler fitting	RTM		Cytec 977-20 epoxy
			window frame	RTM, TFP		
			spoiler fitting	RTM		Cytec 977-20 epoxy
			Passenger door	RTM		Hexflow RTM6-2
			Rear pressure bulkhead			
Airbus	A350 A350XWB		spoilers			
			leading edge of horizontal stabilizer			
			door			
			fan case			
			Rear pressure bulkhead			Solvay PRIFORM

Manufacturer	Aircraft	Aircraft type	Part	Process	Fiber	Resin
Airbus	A320/A320 neo	Narrow-body	Multi-spar flap	RTM		
			wing spoilers	RTM	Teijin Tenax NCF	Hexcel RTM-6
			outboard flap	SQRTM		
			Engine fan blade (GE)	RTM	HexTow IM7	Hexcel RTM
Airbus	A310		Vertical Stabilizer			
Airbus	A220	Narrow-body	Wing skin, stringers, spars		Teijin Tenax	Solvay CYCOM 890
Airbus	A319		Spoilers			
Irkut	MC-21	Narrow-body	Wing skin, spars, stringers	VARTM	Teijin IMS65/Solvay PRISM TX1100	Solvay PRISM EP2400
			wing box			
Comac	919		Engine fan blade	RTM	Hextow IM7	Hexcel RTM

9.1.1 Boeing

9.1.1.1 Boeing 787 Dreamliner

The Boeing 787 is a long-range, wide-body jet, using 27 tons of carbon fiber, 50% of the weight of the aircraft, but most of this is prepreg material. To demonstrate the age of the material, the Toray prepreg material in the empennage, center fuselage, center wing box, wing skins and stiffeners, wing tips, and cargo doors utilizes T800s fiber, were qualified before 2004, and it has been claimed the composite technology is up to 40 years old (Das, Warren, West, & Schexnayder, 2016). The carbon composite allows greater cabin pressure for passenger comfort, larger windows, less corrosion compared to metallic structures, lower maintenance, and lower costs (Brosius, 2007; Creech, 2013).

The 787 was one of the first planes with carbon fiber composite wings and has a resin-infused movable trailing edge, which includes the aileron, flaperon, inboard flap, outboard flap, and 7 spoilers (Gardiner G. , 2021c). These are made using the Boeing patented CAPRI process, using

Hexcel Hexforce 12k spread tow carbon fiber and RTM6 resin (CompositesWorld, 2019a). As of 2016, 10 shipsets per month of the movable trailing edge were being produced, with plans to increase to 14 per month by 2020 (Gardiner G. , 2016d).

The rear pressure bulkhead is also made by a resin infusion process, shared with the A350 XWB (Danobat, n.d.). The Boeing 787 was the first aircraft to use a composite aft pressure bulkhead (Brosius, 2007).

The composite landing gear braces are supplied by Safran, using Hexcel IM-7 fabric and they use an RTM process. Albany Engineering used tufting stitching to produce the preform. This is the first example of a composite landing gear brace – the braces are made of two leg struts holding the landing gear during landing – but is also a flying stitched composite introduced in 2010 (Dell'Anno, et al., 2006).

Latécoère also developed a passenger door using a stitched preform and RTM processing, although it is not clear if it has ever flown (Gardiner G. , 2013).

The process for developing production of the 787 movable trailing edge resin-infused parts is found below to highlight a commercial process for a resin-infused part (Tsotsis, Milham, Howe, & Woods, 2009).

1. ID and verify a stable infusion process
    a. Change infusion strategy for laminate panels with different size and thickness
    b. Process parameter variation study to find operation window and performance
        i. Determine tolerances and acceptable limits for discrepancies
    c. Resin viscosity profiles and reaction kinetics
    d. Resin shelf life and how it affects resin viscosity
    e. Difference between in-plane and out-of-plane permeability
    f. Measuring and controlling pressure differential at the resin flow front
2. Producibility trials -- Move from flat panels to detailed parts
    a. Laying and forming for the dry fabric
    b. Stable resin infusion using boundaries of processing specs
        i. Viscosity range and methods to control resin viscosity

        ii. Prevention and elimination of dry spots and porosity
        iii. Consistent fiber volume fraction (FVF) across the part
            1. Forming can be more important for thickness than infusion
3. Fly-away parts
    a. Pre-production verification
    b. First part qualification
    c. Need to have
        i. People, skills, and knowledge
        ii. Process and instructions
        iii. Material conditioning and control
        iv. Facility and equipment control
4. Struggles going from R&D to manufacturing
    a. Plumbing for the infusion
    b. Monitoring of system controls (leak rate)

9.1.2 Airbus

9.1.2.1 Airbus A220

The Airbus A220 jet is a narrow-body jet, and the composite wing is produced by Spirit Aerosystems in Belfast, Ireland as a legacy product of Bombardier. This wing is a significant milestone for resin-infusion because it is the first flying resin infused wing (Sloan, 2019). The entire wing is not a single unitized structure, but the wing skins, integrated stringers, and spars are made with resin infusion using Teijin TENAX carbon fiber and Cycom (Solvay) 890 resin with a resin transfer infusion (RTI) process (CompositesWorld, 2019a). The infused parts simplify manufacturing of the torque box because it is only 4 parts, the top and lower wing skins and the front and rear spars; also, lowering the part count reduces areas for failure (Solvay, 2019; Gardiner G. , 2021c). The infused parts are AC consolidated. The resin-infused wing has a 10% lower weight than an aluminum wing, 20% lower CO_2, 50% lower NOx, and an expected 20% lower maintenance cost (Nathan, 2019). Further, the environmental penalty of using carbon and epoxy composite parts compared to recyclable aluminum is overcome in just a few hours of flight (Gardiner G. , 2021c; Danobat, n.d.; Nathan, 2019).

The methods used to make this infused wing were forged over decades, starting in the early 2000s with TANGO to produce a 40 ft spar and ALCAS to produce a 40 ft upper wing skin. These large projects helped to identify some of the issues with large-scale composite manufacturing, highlighting the importance of testing large-scale demonstrators to speed up the development cycle (Nathan, 2019). This allows the design to change early in the process while many options are still available before the down selection required when approaching a manufacturing date; this is known as an inverted building block approach. Additionally, there are scaling effects for manufacturing defects that are difficult to model and can be addressed if testing is performed early in the developmental program, as seen here for the A220 wing in Figure 27 (Ilcewicz & Ashforth, 2020; CompositesWorld, 2019a). Alternatively, a conservatively designed (think heavier) large-scale part can be tested without the possibility of changes using a point design process (Ilcewicz & Ashforth, 2020).

Figure 27. Image of Airbus A220 wing

The technical challenges were not the only hurdles for the A220 resin-infused wing: Spirit Belfast also used a developed software package, QUEST, to model the manufacturing process. This helped to eliminate bottlenecks and to train staff. The whole technology package allows for diversification of the technology to other parts of the aircraft, such as tailfins or horizontal tail stabilizers (already used on Bombardier Global 7500 business jet) (Nathan, 2019).

To reach the manufacturing maturation required to produce a resin-infused wing for the A220, Spirit AeroSystems produced a seven-meter wing skin demonstrator that required four hours for the infusion using their Intelligent Resin Infusion System (IRIS). This infusion time is predicted to be the same infusion time for their seventeen-meter wing skin (Sloan, 2021). The IRIS technology "uses specialized tooling, automated material deposition, integrated stringer forming and closely controlled process temperatures… [by] embedding tool-heating technology located close to the mold surface that uses low-voltage resistive heating to provide rapid and precise temperature control" (Sloan, 2020b).

To support the wing skin, a dry reinforcement is being produced by Teijin Carbon Europe in Wuppertal, Germany using 24k carbon fiber. The reinforcement has a unidirectional fabric along with biaxial and triaxial glass fiber patches for drill breakout and corrosion prevention. The same reinforcement technology has already been proven to work in a stringer-forming machine designed by Broetje-Automation in Rastede, Germany. The stringers have "varying thickness, curvature, and blade angles". A single-component resin will be injected at multiple sites to increase the infusion rate and prevent dry spots (Gardiner G. , 2020e).

9.1.2.2 A400M

The A400M, a military transport plane, is important because it had the largest infused Airbus part as of 2010 in the upper cargo door. This is significant because it saved approximately 3,000 metallic rivets by joining the stringers and skin. The infusion used the Airbus VAP process and Hexcel RTM-6 epoxy (Black, 2010). Also, as highlighted in the "Automation of resin infusion processes" section, the A400M used ATL to produce a flat layup at 55 lbs./hr. and then a hot drape-forming process to finalize the preform (Gardiner G. , 2021b).

9.1.2.3 Airbus A380

The Airbus A380 is a wide-body, large aircraft with the last delivery scheduled for 2021 to Emirates (Airbus, 2019). The A380 had the highest mass of composites when it first flew in 2005, thirty metric tons. The rear pressure bulkhead was formed using a resin film infusion process where the dry fabric is laminated with a resin film and then cured (Black, 2004; Gardiner G. , 2021c). The stringers are added and post-cured to "co-cure" the stringers with the already cured layup. RFI is best suited for parts that are "easy" to layup, but it can use the prepreg qualified resins, although it still uses an autoclave for consolidation (CompositesWorld, 2019a). The Hexcel Product Selection Guide shows parts made by RTM for the A380: 16 door hinges using Hexflow RTM-6 and Hexforce G0926 carbon fiber, aileron spar using Hexflow RTM-6 and Injectex woven carbon reinforcement (Hexcel Corporation, 2022; Black, 2003).

9.1.2.4 Airbus A350, A340, A330

The A350, A340, and A330 have the same parts made by resin infusion. The A340 spoiler and the A330 spoiler fitting are made by RTM, using a Solvay (Cytec) 977-20 toughened epoxy, replacing an aluminum piece and saving 15% weight for the A330/A340 and up to 30% for the A350 (CompositesWorld, 2003; Gardiner G. , 2014). The A340 and A350 may use a composite door (Gardiner G. , 2013).

9.1.2.5 Airbus A350

The Airbus A350 is a long-range, wide-body airplane. It uses an RTM door, replacing the aluminum door frame. The door is 6.5 ft tall, 0.3 in wide, and 0.40 in thick. When it was made using LP-RTM it was made from 14 parts and was replaced using HP-RTM to reduce the cycle time from up to 60 min to 20 min, reduced the cost by 30% despite the higher cost of tooling, and used HexFlow RTM6-2, a new two-part epoxy from Hexcel (Gardiner G. , 2019b).

The window frames for the A350 are made using RTM, a large step forward for a primary structure, and have been flying since 2010 (Gardiner G. , 2016e). The window frames are produced using a TFP preform, stitched with selective structural stitches (Fristedt, 2012). They were produced by Advanced Composite Engineering GmbH using a BBG GmbH RTM line, able to produce 8,000 window frames annually. The horizontal stabilizer leading edge is produced using RTM by Aernnova Aerospace, who partnered with ESI to simulate the preform and infusion process to help eliminate dry spots (Gardiner G. , 2016e).

9.1.2.6 Airbus A320neo/A320

The multispar flap is made using RTM by Radius Engineering and consolidated 26 separate prepreg parts into a single piece (Karnozov, 2021; Radius Engineering, Inc., 2023). The outboard flap was produced by a SQRTM process (Gardiner G. , 2021c; Gardiner G. , 2017).

Each wing contains 5 spoilers, and they are made using Teijin Tenax NCF or Hexcel carbon fabric and Hexcel RTM-6 resin. These spoilers are replacing prepreg honeycomb core structures, currently produced by Spirit Aerosystems (Sloan, 2021; Sloan, 2020). RTM was a contender in the business case, including metallic and other composite technologies: ultimately RTM was chosen due to the 30% lower total system cost. Figure 28 shows an image of the spoiler produced by RTM for the A320 (Sloan, 2020).

To produce the wing spoilers, there are four main processes. The process starts with cutting using six automated Schmidt and Heinzmann cutting tables with robots to sort, pick, and place. To ensure quality, the cuts are inspected and then kitted for spot-welding of the thermoplastic binder on the NCF carbon fabric. The takt time is 43 minutes when producing skins and spars separately, with the assembly of the upper and lower skins being the most personnel intensive. These preforms are transferred to seven RTM presses and then to the CNC machine to trim and drill. The total RTM process lasted approximately five hours, including a 356 °F cure for the Hexcel RTM-6 resin.

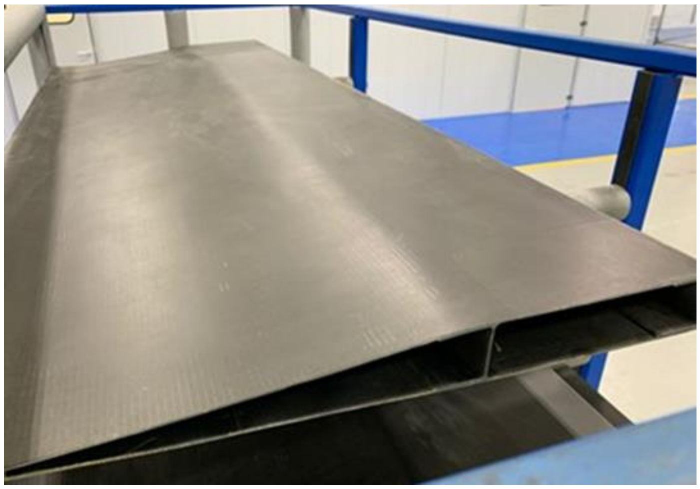


Figure 28. Image of spoiler produced by RTM for the A320
Reproduced with permission from CompositesWorld

The A320 uses the GE LEAP-1 series engine that uses 3-D woven RTM fan blades that save 500 pounds over traditional titanium per engine (Safran Group, n.d.).

9.1.3 Irkut

9.1.3.1 MC-21

A Russian new narrowbody aircraft, the MC-21, is meant to compete with the Boeing 737 and Airbus A320. The resin-infused wing for the MC-21 is very similar to the resin-infused wing for the A220: composite skins and spars are integrated but still employ metallic ribs with fasteners (Boon, 2021). The wing box for the Irkut aircraft is slightly larger than the wing box for the Airbus A220, and it has a length of 59 ft overall. The wing box is 1 inch thick at the root, with further thickness due to the stringers – this is a thick structure for infusion and could struggle with dry spots. Many resins were tested and only the Solvay (Cytec) 977-20 toughened resin was found to successfully infuse the structure. The reliability of the process was highly dependent on the permeability of the system and needed to be consistent over the large size of the part (Gardiner G. , 2021c; Gardiner G. , 2014).

AeroComposit designed and fabricated the infused structures, using a Solvay PRISM TX 100 slit tape with an IMS65 24k UD fiber, Solvay 7720 binder, and the was Solvay PRISM EP 2400 single part toughened epoxy (Sloan, 2018). The dry fiber was laid using AFP equipment from

Coriolis for the wing skins and AFP equipment from MTorres to form the C-shaped spars. MTorres also provided a CNC machine for trimming, routing, drilling, and cutting, along with a jig to assemble the wing skins, spars, and ribs. The stringers were formed from two L-shaped structures using a hot thermoforming process (see section Automated Preforming). The total infusion and cure time is about 24 hours for the wing skins and stringers . The C-shaped spars require 12 hours to produce and are formed as a single structure using tow steering. Further, the aspect ratio is higher for the Irkut wing, 11.5, compared to other narrow-body aircraft, typically 8-9, increasing lift while reducing drag (Karnozov, 2021).

The wing structures are cured in an oven, not an AC like the A220 wing. This means one area of concern for AeroComposit was the risk of porosity. Another concern, due to the size and complexity of the part, was spring-back of the composite part. Working through the development of these structures required modification of the infusion process, which in turn changed the tooling and manufacturing process (Karnozov, 2021).

It is believed that Irkut is about a decade ahead of others in the resin infusion space, possibly withstanding Spirit in Belfast. The Irkut production has hit a setback due to political issues, requiring Irkut to move to composites produced in Russia by Unitech Aerospace (AeroComposit) and may not be able to use the designed engines (Jegley, Przekop, Lovejoy, Rouse, & Wu, 2020). The planned deliveries are as of 2023 (Karnozov, 2021).

9.2 Examples of resin infused parts

Below is a short list of specific parts that have been produced using resin infusion. These are more generalized structures and are not as specific to any OEM or aircraft.

9.2.1 T-shaped stringers

T-shaped stringers are a way to provide increased flexural stiffness while managing weight. Currently, most of these T-shaped stringers are attached to the wing skin with mechanical fasteners or co-cured using prepreg materials. Co-curing allows separate prepreg parts to be cured together to help eliminate fasteners but still requires an autoclave. Automated methodology to produce wing skins is not well suited to stringer production because the T-shape is a relatively complicated structure, has a high aspect ratio, and needs fiber layup in the off-axis direction (Li, Yao, Liu, Chen, & Dai, 2008; Fauster, Schillfahrt, Hueber, & Schledjewski, 2017).

There has been extensive infusion development for T-shaped stringers for the difficulties identified above. For example, the Wing of Tomorrow (WOT) and Clean Sky 2 projects performed such work and highlights the joint effort of many industrial partners, but also government-backed public research institutions, such as the National Composites Center in Bristol, England. The WOT project used a continuous process (see previous section) to produce a stringer. Spirit had produced a 23 ft and 56 ft wing skin with integrated stringers, a possible demonstrator for an A320 replacement. To do this, Spirit developed specialized tooling and automated material deposition for the wing and integrated skins (Sloan, 2021). The goal is to attain the main advantages of resin infusion: simpler assembly and less fasteners. The 56 ft wing skin was expected to require 4 hours to infuse (Budwal, Kasper, Goering, & Ward, 2020).

9.2.2 Doors

A door made using resin infusion is important because it is a primary structure that requires load-carrying redundancy. Figure 29 (Gardiner G. , 2013) shows a concept door produced by Cyclone, LTD that unitized the door, eliminating all fasteners, and was able to reduce cost and weight by 30% compared to an aluminum door (Gardiner G. , 2016f). To meet the toughness requirements, a Huntsman XU3508 resin was used that has a “multiphase toughening technology”. This was a step in the technology because infused doors produced by Latécoère and Eurocopter connected the skins and beams, ribs, and stiffeners, with metallic fasteners (Gardiner G. , 2013). The Latécoère RTM door was very complicated, requiring 45 separate subpreforms that required stitching (Gardiner G. , 2013).

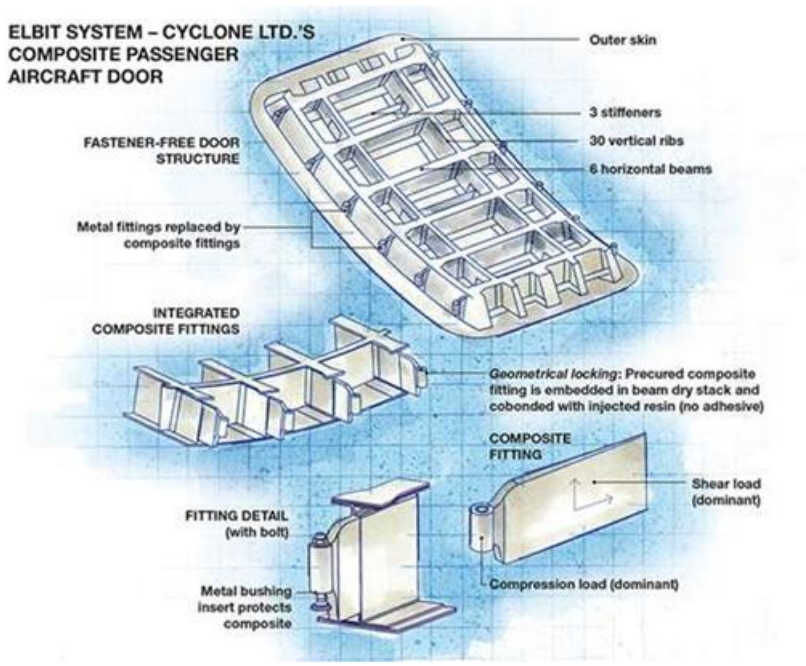


Figure 29. Door made by Cyclone, LTD

Reproduced with permission from CompositesWorld

9.2.3 Engine fan blade

Although not much can be found in the literature about the LEAP fan blade produced by CFM, a joint company between GE and Safran, what can be learned is that a 3-D woven stitched fan blade is produced using RTM, saving 500 pounds (Jewell, Soret, Bradley, & Ahmed Almahmood, 2009). According to Safran's website various iterations of the LEAP engine power the Airbus A320neo, Boeing 737 MAX, and the Comac C919. There have been more than 20,000 fan blades produced (Jewell & Soret, 2019).

9.2.4 Resin-infused wing box progression

Ginger Gardiner published an article in Composites World that demonstrated the progression of a resin-infused wing box, starting in 2013 by GKN Aerospace (Gardiner G. , 2021c). This wing box was able to eliminate fasteners, a typical advantage of resin infusion, when joining the stiffened skins and various shaped stringers. The first resin-infused wing occurred at the same time with Bombardier first testing resin-infused wings for the eventual Airbus A220, but this still was consolidated in an AC. In 2017 OEM Irkut took the next step forward and produced a wing very similar to the Airbus A220 wing but decided to forgo the AC by using only vacuum bag consolidation. Airbus unveiled a half-scale demonstrator in 2017 of a resin infused center wing box for the A320 with plans to produce a full-scale demonstrator in 2019.

9.3 Examples of stitched aircraft parts

Only three examples of stitched resin-infused composites could be found: the Airbus A380 rear pressure bulkhead, the Boeing 787 landing gear brace, and the military C-17 landing gear door. The A380 rear pressure bulkhead is relatively large, 8 m, used a stitched multiaxial fabric using a single-sided blind stitchand infused by a resin film infusion process (Jegley, et al., 2015; Brandt, Filsinger, & Gessler, 2005).

The Boeing 787 landing gear bracket has already been discussed.Very little can be found about the stitching in the C-17 landing gear door. The first doors were delivered in 2009 as a replacement of prepreg parts that were not meeting the required performance, produced by General Dynamics (Creech, 2013).

10 Future use of resin infusion in aircraft

10.1 Boeing

It is expected resin infusion will not replace current flying structures but will be implemented on new aircraft because the sunk costs of the prepreg infrastructure make users lean on the familiar – unless of course failures occur, necessitating updated solutions. Newer technologies that can economically compete with current technology can be included in new aircraft as materials and processes are defined but there will be a departure from current infrastructure, sometimes significant, that will require a very strong business case. As Airbus has already claimed next generation aircraft may be a blended wing body design, they will need to qualify the materials and processes by ~2025, based on previous development timelines.

Boeing has shown a smaller deviation from the current aircraft, the transonic truss-braced wing aircraft. Figure 30 shows the Boeing transonic truss-brace aircraft that has thinner but longer wings to help reduce emissions by up to 30% (Gardiner G. , 2023).

Figure 30. Concept of Boeing Transonic Truss-Braced Wing (TTBW) configuration
Reproduced with permission from Composites World and Boeing

10.1.1 Unmanned X-48

Boeing has been showing examples of blended wing body aircraft for years, including the unmanned X-48, a joint project with NASA that flew more than 122 flights over several years to help prove the technology, starting in 2010. The X-48 aircraft (seen in Figure 31) was moderately sized, had a 6.4 m wingspan, a stitched resin-infused test bed, and was built by Cranfield Aerospace (Creech, 2013; Smock, 2011). The X-48 was the proving ground that led to a large-scale demonstrator of the PRSEUS and blended wind body tested at NASA (Sherman, 2016).

Figure 31. Boeing X-48
Reproduced from Wikipedia
https://en.wikipedia.org/wiki/Boeing_X-48

10.1.2 Loyal Wingman

Following in the footsteps of the X-48 test mule, the Boeing Loyal Wingman uses the largest resin-infused part produced by Boeing. The aircraft is similar in size to the X-48 at 11.7 m long and a wingspan of 7.3m (Airforce Technology, 2023). Also, the aircraft was able to move from design to flying in three years, very fast for an aero application, and shows how computer design can help to aid the speed of development (Institution of Mechanical Engineers, 2020; Nehls, 2021).

10.2 Airbus

Airbus plans to have a "Zero e" airplane flying by 2035, using hybrid hydrogen propulsion with the goal to reduce CO_2 by 50%. A full-scale prototype is planned to be unveiled by the late 2020s and they showed three separate concept aircraft: a turbofan, a turboprop, and a blended wing body. It is expected that SRI is an enabling technology for the blended wing body because it can provide a composite solution that meets the weight requirements, unlike prepreg.

11 Other industries that use resin infusion

There are many markets that use resin infusion, and they are identified with brief examples below.

11.1 Automotive

11.1.1 Carbon revolutions

Carbon Revolutions is based in Australia and is making resin-infused wheels for automotive applications.

11.1.2 McLaren automotive

McLaren is heavily invested in RTM processes, including an RTM monocell for many of their cars. They use fast-curing Huntsman automotive resins that do not have the mechanical properties required for aerospace. The RTM technology has progressed enough that they recently opened a McLaren Composites Tech Center to further develop their RTM processes (Griffiths, 2010; Moore, 2020).

11.1.3 Lamborghini

The Lamborghini Aventador LF-700 used a resin-infused chassis, again using Huntsman resins. They also used Forged Composites, where chopped fiber is pressed, even studying this technology for the use for connecting rods. Forged Composites have been used in the Boeing 787 for window frames, gussets, and rib reinforcements (Sherman, 2016).

11.1.4 BMW

BMW has the most widespread use of RTM carbon composites. The i3 had many body parts, including the monocoque cell, made from RTM. The 7series used many different types of RTM processes (BMW Group PressClub, 2010; Gardiner G. , 2016c).

11.2 Marine

The marine space has been using resin infusion for many decades. One brief example was a recent record of a 140 ft boat hull performed as a single infusion (Soundings Online, 2019).

11.3 Wind energy

Wind energy and marine have more heavily adopted resin infusion processes than aerospace has. One example is LM Wind Power that built a 290 ft wind blade using a VARTM process (Dawson, 2018).

11.4 Aerospace

An identified future of aerospace is in urban air mobility (UAM). The UAM space has > 100 companies working in this space, but they do not have the inertia or history that large aerospace companies have and are more in line with a disruptor like Tesla, Rivian, and other novel electric vehicle manufactures (Sloan, 2021). While they do not have the capital of a large OEM, they have the design freedom to choose whichever technology is best for each application. The relatively small footprint would make them very amenable to an RTM process to make many parts quickly, but also amenable to an infusion process to help lower capital expenditures.

12 Patents

To gain a better understanding of how investment into resin infusion processes has changed over time, Google Patents was searched for keywords associated with resin infusion in the claim section for the US, EU, and Australia. There was a long list of keywords searched, including keywords for both VARTM and RTM processes. World patents were not investigated because a world patent is not always a focus; also, there can be overlap with counting the number of hits and duplicates of a single patent will not accurately reflect the number of patents filed. Boeing has a clear lead in the number of patents related to resin infusion (Figure 32). This was expected as Boeing has a long history, as far back as the mid-1980s, of work related to resin infusion. The number of patents per year has been steadily increasing (Figure 34), suggesting further investment from the aerospace market into resin infusion processes. When investigating resin infusion patents assigned to others besides Boeing and Airbus, GE was a clear leader in the space (Figure 33).

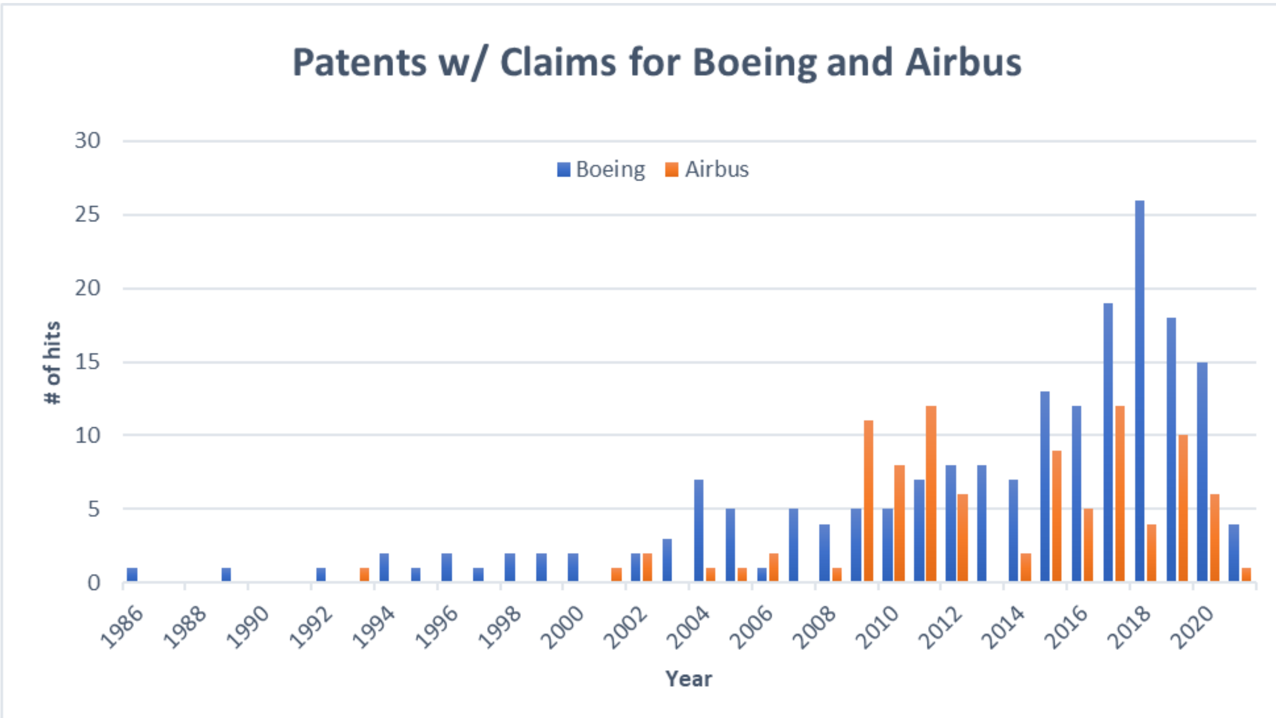


Figure 32. Patent hits for resin infusion for US, EU, and Australia for Boeing and Airbus

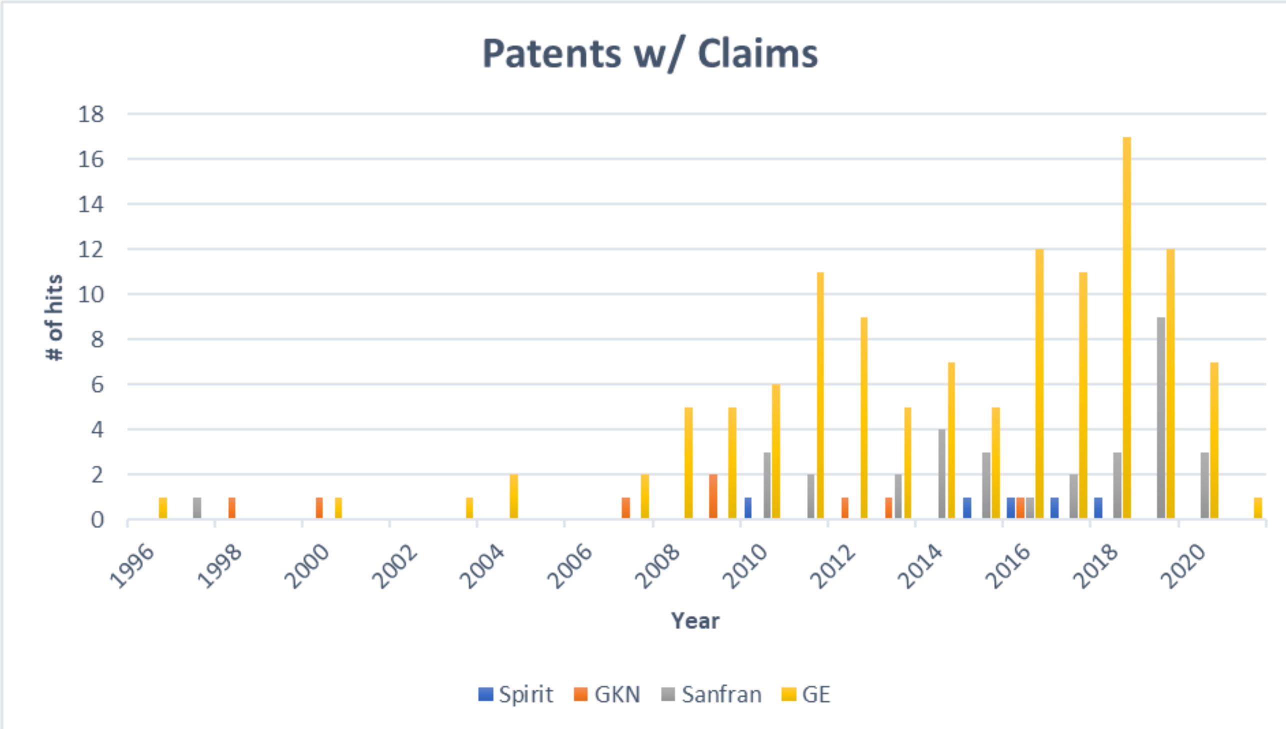


Figure 33. Patent hits for resin infusion for Spirit Aerosystems, GKN Aerospace, Sanfran, and GE

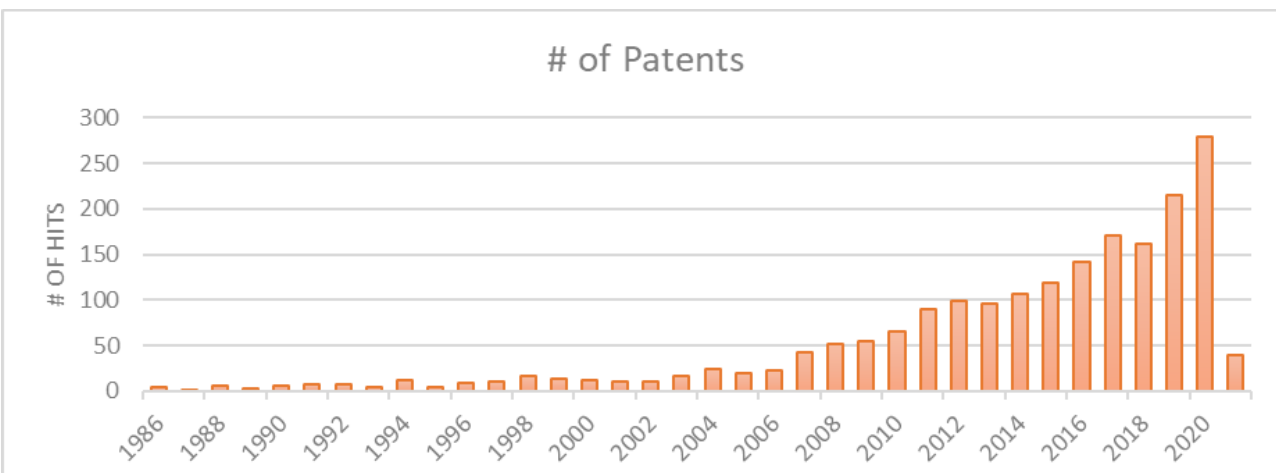


Figure 34. Total number of patent hits for resin infusion over time

13 Qualification of materials

13.1 Process for qualification of new materials/process

Resin infusion presents a new challenge when it comes to qualifying material. The topic of requiring both the resin and the fabric to be qualified has been identified many times in our market interviews. When purchasing prepreg, the material arrives with a certificate of analysis (COA) that outlines the quality checks for the material. For example, the FAA has guidelines for the characterization of prepregs that include aerial weight, resin weight percent, tackiness, volatile content, flow, gel time, chemical reactivity, tack, and drape. It is unclear how a resin infusion process can test all these characteristics and how to collect and design for variability (McCarvill, Ward, Bogucki, & Tomblin, 2003).

All aerospace materials need to meet specific regulations before they are accepted to fly. Specific regulations include 14 CFR §2X.603 for material control, §2X.605 for fabrication methods, and §2X.613 for material strength properties and material design values.

13.2 National Center for Advanced Materials Performance (NCAMP)

One of the most repeated issues during our interviews related to resin infusion adoption for aerospace was the lack of a publicly available materials database. NCAMP has such a resource, but the number of materials qualified is very low: there are seven thermoset prepreg materials (three Solvay, one Hexcel, two Toray, one Newport, one additive manufactured material, and one thermoplastic material). NCAMP is part of the National Institute for Aviation Research (NIAR) at Wichita State University. A recent addition to the NCAMP website shows two resin infusion material systems are going through the process: Hexcel HiTape dry fabric with Hexcel Hexflow 1078-1 resin and Teijin Tenax NCF fabric with Solvay EP2400 resin.

The process of how to qualify materials through NCAMP is found in Figure 35 (Ng & Tomblin, 2017). It is a complicated flowchart, and it will require lots of testing to get a material NCAMP-qualified – it could take a thousand panels to have the required statistics to fully qualify a material. The advantage of having NCAMP-qualified materials is that base material testing has been completed and allows for faster and more economical equivalence testing to be completed. This does not negate the necessity to qualify the part using the NCAMP materials, but it does significantly decrease the cost and time commitment. A large OEM typically qualifies their own material with the FAA separately from the NCAMP database and can cope with the cost of qualification; however, this does not diminish the impact of the significant cost to qualify materials, requiring a strong business case to proceed with qualification. A pathway to populate the NCAMP database may be a joint program between aircraft producers, the public sector, and raw material suppliers to help share the cost burden and improve the business case economics. The NCAMP database will likely be most used by smaller aircraft manufacturers, i.e., UAM or unmanned aerial vehicle (UAV), companies that do not have the inertia and history of prepregs.

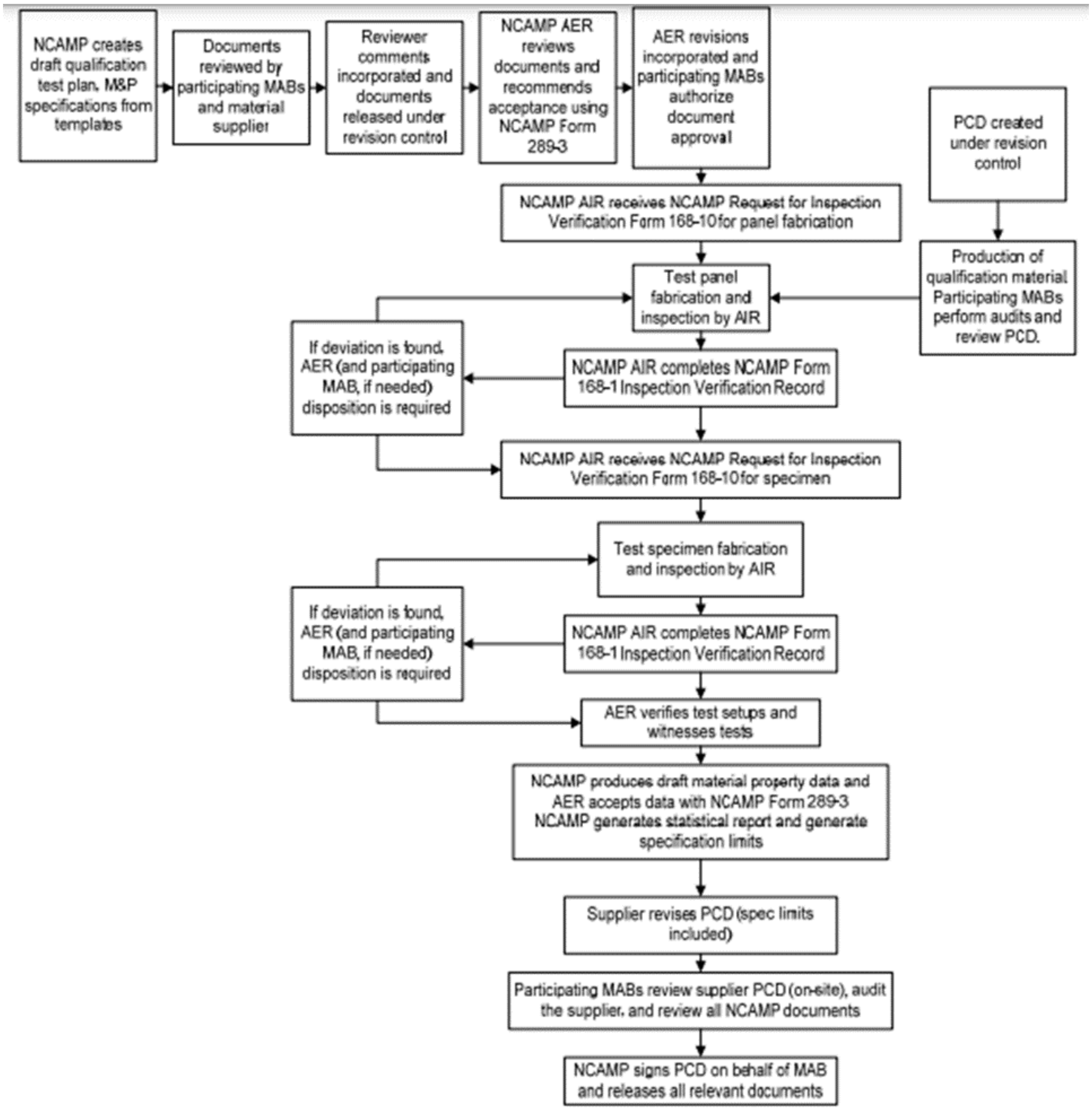


Figure 35. Material qualification and property data acquisition from NCAMP SOP
Reproduced from NCAMP SOP NSP 100

Attaining NCAMP qualification for a small subset of relevant raw material products is the only economical way to gain qualification for resin-infused parts due to the massive complexity of resin infusion compared to prepregs. There are many different types of dry fabrics, layups, and resins to choose from – there is no way to fully qualify every single possibility. Therefore, the most industrially relevant materials will need to be qualified.

14 Market reports

14.1 Lucintel

A market report provided by Lucintel showed the global market for aerospace composites was about 37 million pounds, $8.7 billion in 2020, of which only 2.4% by volume was resin infusion with small growth to 2.7% by 2025. The market value in 2025 is expected to be 1.3 million pounds ($213 million), up from 0.9 million pounds ($147 million) in 2020.

The drivers to move to resin infusion are lower manufacturing time, lower cost, low void content, better dimensional stability, and increased aircraft deliveries compared to an autoclave cure composite. The market is split between RTM and VARTM processes. The dominance of prepreg, lack of technical knowledge, certification, recyclability, and the issues with producing a dry fabric part are reasons why resin infusion has not been adopted (Figure 36).

Barriers for Growth	Key Considerations
Strong Competing Technology	Autoclave is a long-established process for aerospace manufacturing. There is a perception that other processes cannot produce mechanical performance like autoclave
Resin Uniformity	In the RTM process, control of resin uniformity is difficult as radii and edges tend to be resin rich
High Tooling Cost and Process Development Time	RTM is difficult to justify in large-sized, low volume, and high complexity parts due to the high tooling costs
Repair and Recyclability	There is a requirement for repair and recyclability, and thermoplastics are becoming the material of choice, creating hurdles for infusion technologies to penetrate in this market

Figure 36. Barriers for resin infusion growth

Lucintel also investigated which aircraft parts are best suited for resin infusion processes as seen in Figure 37 and Figure 38.

Figure 37. Aircraft parts best suited for resin infusion processes (from Lucintel)

Figure 38. Aircraft parts comparison for RTM and VARTM processes (from Lucintel)

Figure 39 shows flying examples of resin infusion from Lucintel.

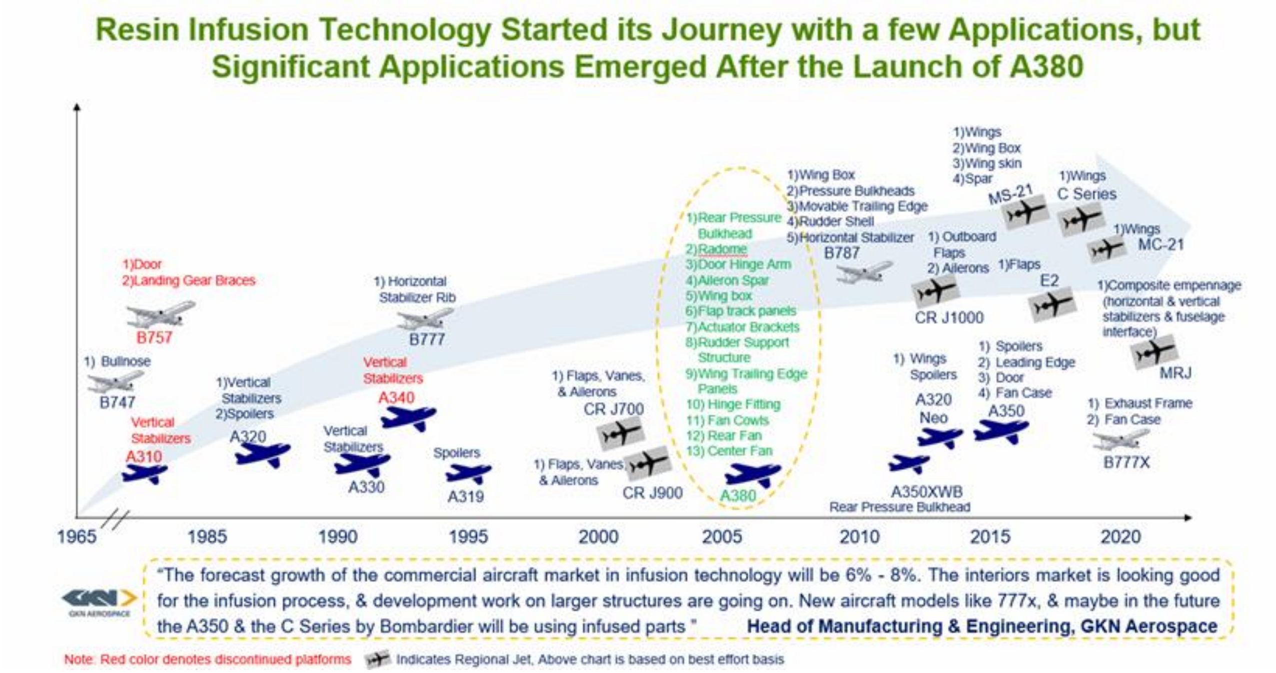


Figure 39. Flying examples of resin infused aircraft parts (from Lucintel)

One significant issue preventing the adoption of resin infusion is the lack of industry experience; understanding of a prepreg process does not equate to understanding a resin infusion process. A quote from an interviewee that is the head of manufacturing and engineering is “development work on larger structures looks impressive. Barriers in this market are training, knowledge, and expertise, especially in design and manufacture and material qualification by the OEMs”.

14.2 Aeronautics Research Mission Directorate (ARMD) workshop

A report published by NASA in November 2019 highlights the information presented in an Aeronautics Research Mission Directorate (ARMD) workshop about the rapid manufacturing of composites for commercial and urban aviation. The purpose was to understand the state of the technology, understand technology gaps, and determine investment areas for NASA. NASA asked for market involvement to determine the importance and detailed info for different technology foci. Table 16 is adapted from Ransom et al. (Ransom, Glaessgen, & Jensen, 2019). It shows results from the market survey performed for the NASA ARMD workshop on materials and methods for rapid manufacturing and urban aviation.

The green items show the most important and very important topics, orange is of somewhat important , yellow is of not very importance, and red is of least importance.

Table 16. Results from market survey performed for NASA ARMD workshop

Technology Focus	Importance	Detail Task
Design and analyze utilized and bonded structural concepts	Not Very Important	Conduct trade studies with industry to determine most promising use of unitization for rapid manufacture of CFRP structure needed for next gen 737 which meets throughput while minimizing defects/repairs/and scrap rates.
	Very Important	Develop NDE techniques for assessment of complex unitized structure.
	Very Important	Develop robust and certifiable bonding techniques for bonded structure. (see also “Cross-Cutting Technologies” below)
	Not Very Important	Develop tooling concepts and processing techniques for rapid manufacture of unitized structure.
Develop technologies to increase Thermoset composite production rates for aerospace structure	Not Very Important	Conduct trade studies to determine most promising processes to rapidly manufacture thermoset CFRP structure for next gen aircraft while minimizing defects/repairs/scrap parts.
	Not Very Important	Further develop/tailor existing COTS physics-based process models to identify key thermoset material properties for rapid AFP manufacturing.
	Very Important	Further develop/tailor existing COTS physics-based process models to identify key thermoset material properties for rapid infusion materials.
	Not Very Important	Further develop/tailor existing COTS physics-based process models to identify key thermoset material properties for rapid Out of Autoclave Vacuum Bag Only manufacturing.
	Not Very Important	Partner with OEM and Material Suppliers to develop fast curing resins tailored for AFP with OOA VBO processing.
	Somewhat Important	Partner with OEM and Material Suppliers to develop fast curing resins tailored for the RTM infusion process.
	Not Very Important	Partner with OEM and Material Suppliers to develop fast curing resins tailored for the VARTM infusion process.
	Very Important	Partner with OEM and Material Suppliers to develop fast curing thermoset resins tailored for AFP with autoclave cure.
Develop technologies to increase Thermoplastic composite production	Most Important	Partner with OEM and Material Suppliers to develop thermoplastic resins tailored for in-situ automated placement processing.

Technology Focus	Importance	Detail Task
rates for aerospace structure	Most Important	Demonstrate closed loop control for in-situ process fabrication for real-time build inspection, geometric accuracy, and rework/repair for thermoplastic CFRP structure.
	Not Very Important	Demonstrate tool-less OOA fabrication of a representative complex aerospace-quality thermoplastic structure.
	Very Important	Determine effect that thermoplastic prepreg tape surface has on bond quality of the composite during build lay-up.
	Somewhat Important	Demonstrate the integration of prefabricated components into a thermoplastic composite, multi-material structure during build. Examples include thermoset parts, metal parts, etc. as subcomponents of a thermoplastic structure.
Develop In-Process Monitoring/NDE technologies to increase composite production rates for aerospace structure.	Very Important	Develop Real Time Process Monitoring and Control for material tracking/process monitoring/ digital thread at every step from material acceptance/screening through delivery/service. In-situ process monitoring is needed to reduce material variability, to detect FOD (e.g., net poly backing paper) during lay-down and to perform cure monitoring especially about new material systems and architectures.
	Not Very Important	Develop tools for more rapid assembly of parts with real-time feedback maintaining correct positioning/quality, geometry, dimensioning, and tolerance tracking throughout assembly via computer vision/photogrammetry analysis.
	Very Important	Develop rapid NDE techniques including large scale automated thermal inspection, computer simulation aided inspection of problematic geometries, and simulation for design-for inspect ability.
	Most Important	Develop automated inspection data analysis tools for rapid manufacturing including automated in-situ defect recognition/quantification/ characterization, linking NDI results to material state for quick/informed decisions, and machine learning based parameter estimation for process efficiency improvement/variability reduction
Develop Process Modeling and Simulation technologies to increase composite production rates for aerospace structure.	Very Important	Develop software tools to predict processing defects (deposition, cure, forming, resin transfer, etc.) to reduce time and cost to develop new composite manufacturing processes and to optimize current processes for rate and yield.
	Somewhat Important	Develop and validate tools to predict material properties using atomistic to continuum level modeling. Characterize new materials for implementation in modeling tools (NCAMP-like task) and validation of material models.

Technology Focus	Importance	Detail Task
	Least Important	Provide a stable source for storage and distribution of available software tools. Manage documentation of software manuals, training and data for software tools.
	Least Important	Development of software tools to crease a contiguous digital thread for aircraft manufacture from design through product service.
Develop Testing Requirements for Rapid Manufacturing/Increased Production Rates	Somewhat Important	Determine new test methods and/or modifications to existing methods required to generate experimental input data for design analysis framework.
	Somewhat Important	Assess the suitability of existing standards and develop new methods where needed to fully characterize materials for rapid manufacturing.
	Not Very Important	Develop test methods required for input properties for multiscale model validation.
	Not Very Important	Develop advanced testing methodology to reduce the time/cost of coupon test programs for new materials insertion.
	Not Very Important	Develop test methodologies to characterize bonded joints.

14.3 Stratview research

A market report was purchased from Stratview Research that covered the market size in more depth. Figure 40 and Figure 41 discuss the different ancillary materials required for resin infusion and the different companies providing the ancillaries. The relative size of different composite technologies is found in Figure 42.

Figure 43 shows the world market size for resin infusion; Stratview suggests the large resin infusion presence in Asia-Pacific is due to wind energy.

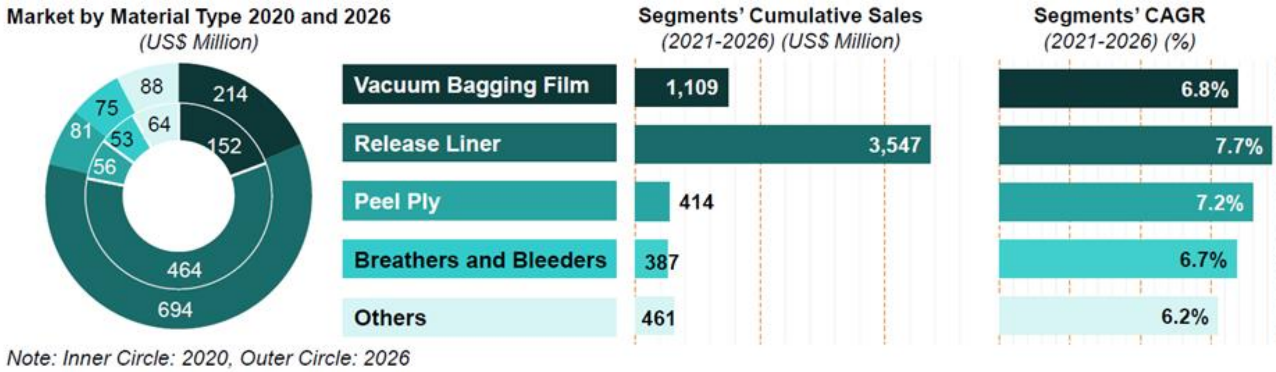


Figure 40. Composite process materials market by material type (from Stratview Research)

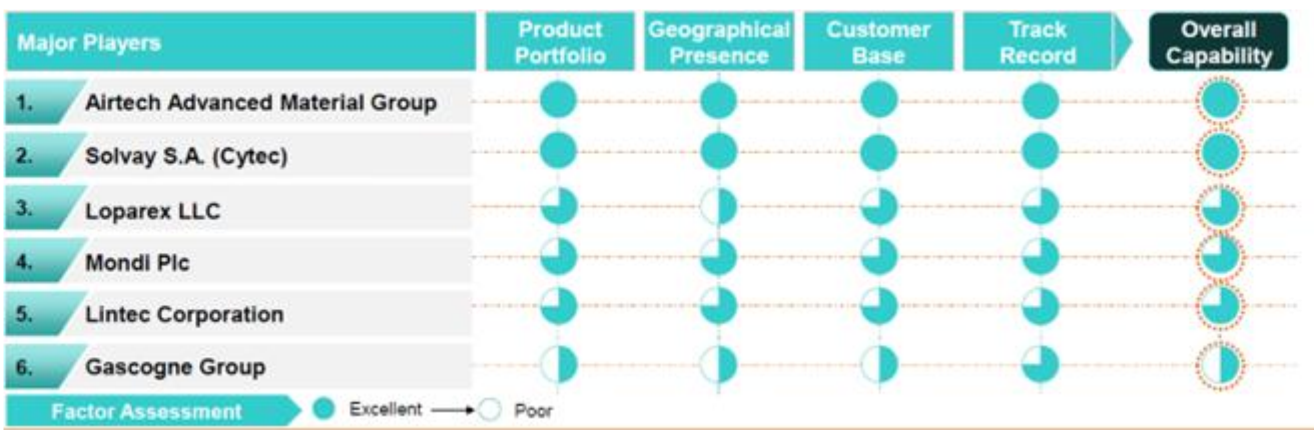


Figure 41. Composite process material market information (from Stratview Research)

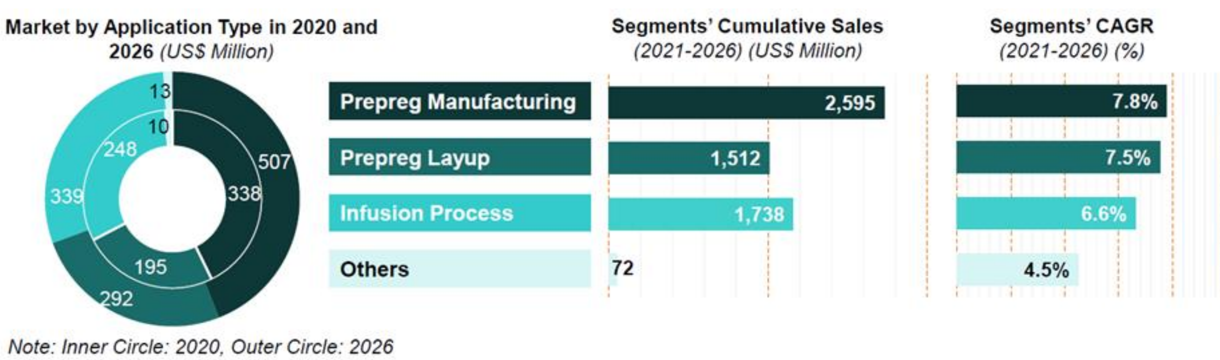


Figure 42. Composite process materials market by application type (from Stratview Research)

Figure 43. Composite process materials market for infusion (from Stratview Research)

15 Review of literature

15.1 Progress in infusion of raw materials

Through the market interviews that occurred while writing this document, several issues related to raw materials were identified as widespread in the market. The first discussed is the perceived lack of a toughed infusion resin. Toughening can occur through the addition of rubber particles, which can be filtered by the dry fabric during the infusion process, or by a thermoplastic veil or binder included on the dry fabric. Both options can cause incompatibility between the thermoplastic toughener and the epoxy to become a source of failure. Hexcel has demonstrated the capability of updated tapes and fabrics to meet or exceed the performance of prepregs. Figure 44 shows a comparison for a resin-infused part compared to a IM7/8552 prepreg. The Hexcel HiTape® is meant for AFP/ATL and Himax® is a dry fabric meant sold in 60 in wide rolls (Hexcel Corporation, 2020). As seen in Figure 44, the physical properties included are unnotched tension (UnT), open-hole tension (OHT), unnotched compression (UnC), open-hole compression (OHC), beam test (BEA), and compression after impact (CAI). Hexcel also demonstrated the fracture toughness of a HiTape® can be higher than bonded prepregs for a coupon sample as seen in Figure 45 (Hexcel Corporation, 2020).

Solvay also has product offerings that use particulate tougheners that are not filtered during the infusion process and can meet or exceed the measured performance of prepregs, as seen in Figure 46.

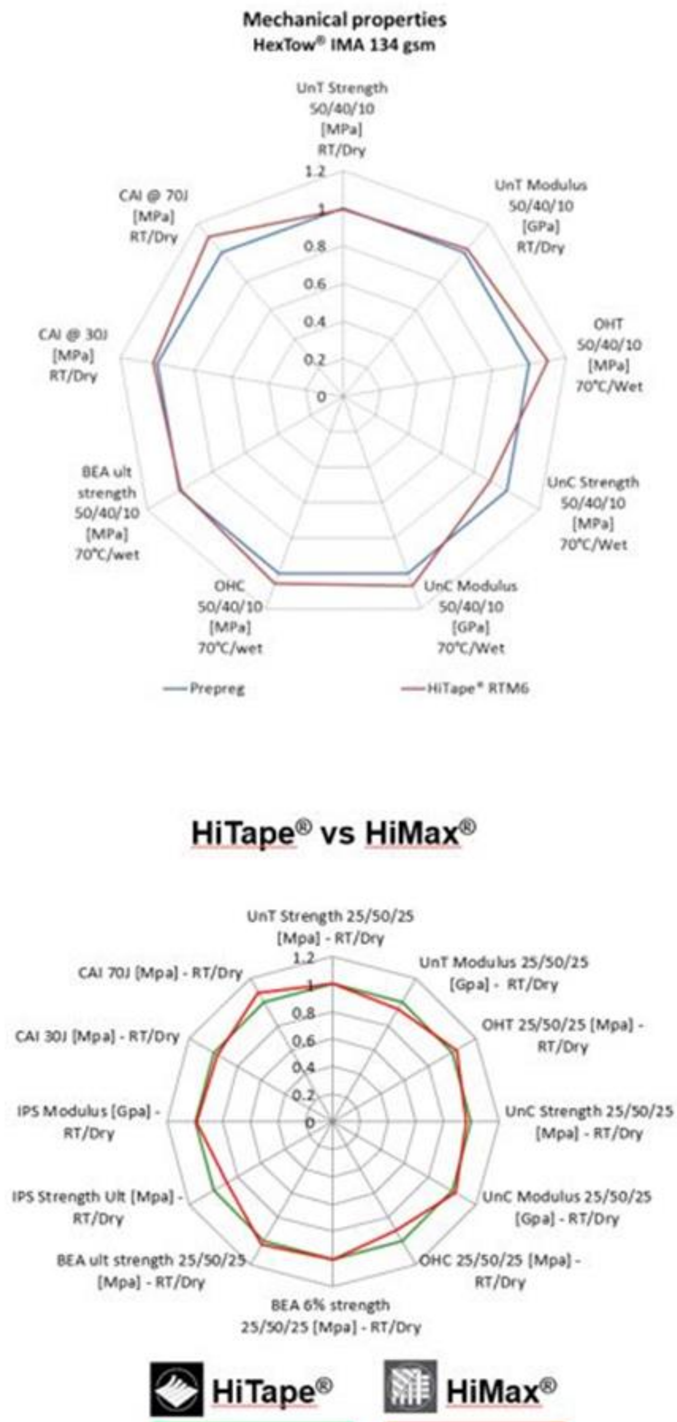


Figure 44. Comparison of Hexcel HiTape® RTM6 and prepreg carbon fiber (top) and Comparison of HiTape® and HiMax® (bottom)

Reproduced with permission from Hexcel

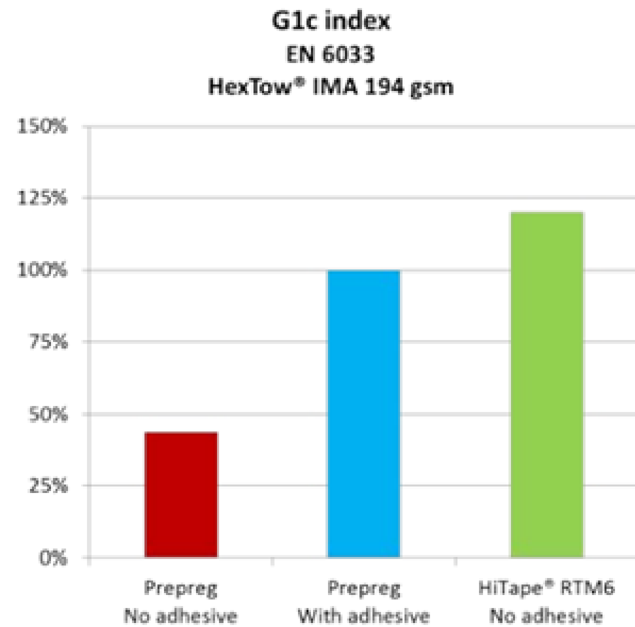


Figure 45. Comparison of fracture toughness (GIC) for prepreg, bonded prepreg, and HiTape®

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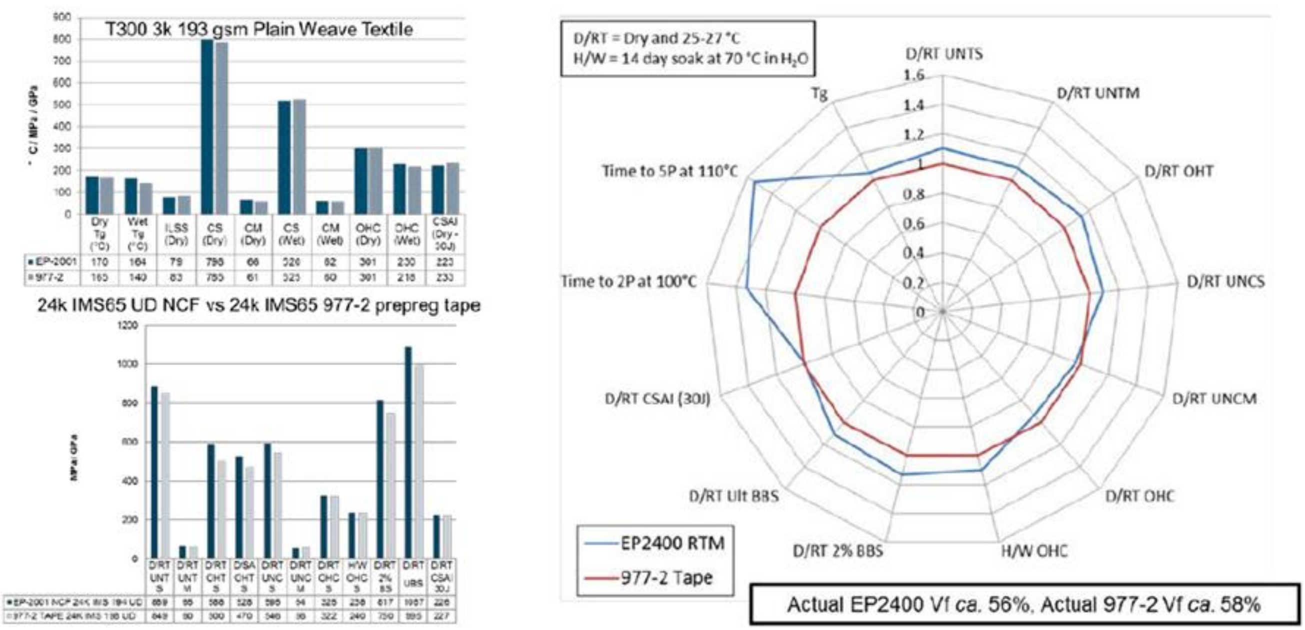

Figure 46. Comparison of prepreg and infusion mechanical properties for a new EP2400 RTM

Infused part and plain NCF textile (blue line on right side)

977-2 prepreg tape part (red line on right side)

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The aerospace resins currently used are quite old -- in the case of Hexcel RTM6, it is decades old. Updated resin systems for adjacent markets have been developed with a rapid cure. For example, the automotive market has shown a dramatic decrease in cure time, up to 30 seconds for a 0.04-0.2 in thick part using a Huntsman Araldite® resin system. While it is understood automotive resins do not have the performance of aerospace grade resin, it does show there is room for the chemistry to develop. Our market interviews uncovered the desire for a fast-curing, long pot-life resin system. The resin formulators should be able to meet this desire with a stronger business case (Malnati & Sloan, 2018).

Spread tow fabrics are also a technology provided by TeXtreme, Hexcel, and others that have only seen partial adoption. Spread tow fabrics flatten the typical round tows into flat layers, significantly decreasing the thickness of the fabric. They can be provided as UD tapes or biaxial/multiaxial versions. One advantage of spread tow fabrics is the decreased crimp along the fibers, increasing the compressive strength. Additionally, the thin layers help prevent microcracking, and may aid stitched resin-infused composites. TeXtreme has the capability to engineer highly controlled separation between the spread tows to help with Z-axis permeability and TeXtreme also has a proprietary technology to monitor every inch of carbon produced to ensure repeatability in the separation (Sihn, Kim, Kawabe, & Tsai, 2007).

15.2 Published advantages of composites

The published advantages of composites compared to metals are commonly known: a higher specific strength, lower corrosion, and less maintenance, among others. A summary table, highlighting high-level advantages and disadvantages for multiple composite materials is found in Table 17.

Table 17. High-level advantages and disadvantages for multiple composite technologies

	Prepreg		**Z-pinned prepreg**		**VARTM (above infusion alone)**		**SRI (above infusion alone)**
Advantage	High quality	Eliminate AC	Increased fracture toughness	Unitization	Lower cost tooling than RTM	Tight control of FVF	Manufacturing aid for dry fabric stacks
	Consistent FVF	Low porosity	Increased delamination resistance	Eliminate AC	Low chance of fiber wash	Very high production rate	Increased fracture toughness
	Low porosity	FVF is close to AC prepreg	Increased strength	Equivalent performance as prepreg		Mold surface on both sides of part	Increased delamination resistance
	Automated layup		Increased post-impact properties	Lower raw material cost		Consolidation aided by press	Increased strength
	Manufacturing facilities already in place			Lower weight			Increased post-impact properties
				Higher production rate			Increased Z-direction permeability
				Reduced waste cost			
				No out-time for fabric			
				Automated layup			
Dis-advantage	High CapEX	Possible lower consolidation (microporosity, bubbles)	Fiber waviness	Become own prepreger	Higher consumable cost than RTM	More expensive tooling	Microcracking
	Autoclave	Cold storage	Fiber breakage	Poor dry fabric wet-out can cause porosity	Only 1 side of part has mold surface	Complicated tooling	An additional manufacturing step
	Nitrogen cost for AC	Short out-time	Lower in-plane properties	Lower toughness	Vacuum failure is catastrophic	Possible fiber wash at injection point	Change in FVF at stitch location
	Cold storage	Loss of tack with increased out-time	Decreased FVF	Race tracking of resin	Consolidate only with vacuum	Expensive press required	Stitching and cure tooling required
	Short out-time		Prevents full consolidation	Possible lower consolidation			
	Long cure time		Microcracking				
	Higher waste cost (resin + fabric)		Difficult to administer				

15.3 Published disadvantages of composites

Some disadvantages of composites are the much weaker Z-axis (through-the-thickness) direction for stiffness, strength, and interlaminar shear strength and toughness. These disadvantages push composites towards high in-plane performance applications but can increase the weight to ameliorate design risk. Impact properties can be low, dramatically so for subsequent impacts (Mouritz, Bannister, Falzon, & Leong, 1999). Raw material producers have addressed these issues to a satisfactory level for prepregs, but resin-infused parts fall behind unless toughening veils (like for Hexcel HiTape® and HiMax®) or toughened resins are employed.

Other issues are composites can be expensive to produce, either due to manufacturing processes or raw material waste, unacceptable part failure rates, and quality requirements. Raw material waste can be 30% or more and expensive automation processes were required to lower scrap and increase quality.

15.4 Published advantages of prepreg

15.4.1 Autoclave prepregs

Resin infusion was initially suggested to be a viable future technology due to some of the limitations of prepregs: the necessity of an AC curing cycle; however, the AC is not always the bottleneck, it can be machining, assembly, or rework of parts that failed quality inspection (Gardiner G. , 2021b). Ultimately, prepregs are qualified for primary aerospace applications because they have tightly controlled quality, a highly consistent fiber volume fraction, and very low porosity (CompositesWorld, 2019a). Because of the higher efficiency, high quality, performance, safety, and increased profitability compared to wet layup, prepregs have a mountain of data to aid qualification (Sloan, 2018). Prepregs also have a very high fiber volume fraction, up to 65% (Bishop, Brian; TCR Composites, 2020; González, Vilatela, Molina-Aldareguia, Lopes, & LLorca, 2017).

15.5 Published disadvantages of prepreg

15.5.1 Autoclave prepregs

Prepreg has many disadvantages and is why research is dedicated to overcoming these issues. The most common complaint for prepregs is the high capital cost. The AC requires high CAPEX to purchase, large areas to house the AC, high recurrent costs for energy and nitrogen, and the resins require long cure times. Additionally, automation systems, such as ATL and AFP, are very expensive and have limited flexibility (González, Vilatela, Molina-Aldareguia, Lopes, & LLorca, 2017; Das, Warren, West, & Schexnayder, 2016). Prepregs can have a high amount of wasted carbon: manufacturing waste of 6-19%, uncured prepreg up to 70% of waste stream, ply cutter scrap of 25-50%, and a post processing of 2-40%. To further increase the costs, hand layup of prepregs can have poor quality, large variability, and high labor costs (Nilakantan & Nutt, 2018). Prepregs also require cold storage as the resin is partially cured, limiting shelf life and the out-time (less than 30 days). A short out-life means parts must be produced quickly to not cure before the AC. Last, prepregs may struggle with highly complicated shapes, highlighted in Figure 47, showing porosity in a prepreg in a corner bend (Sloan, 2017; Dorworth, 2021). The ILSS is dictated by the resin in tight radii, unless it can be increased by through-the-thickness reinforcement, i.e., Z-pinning.

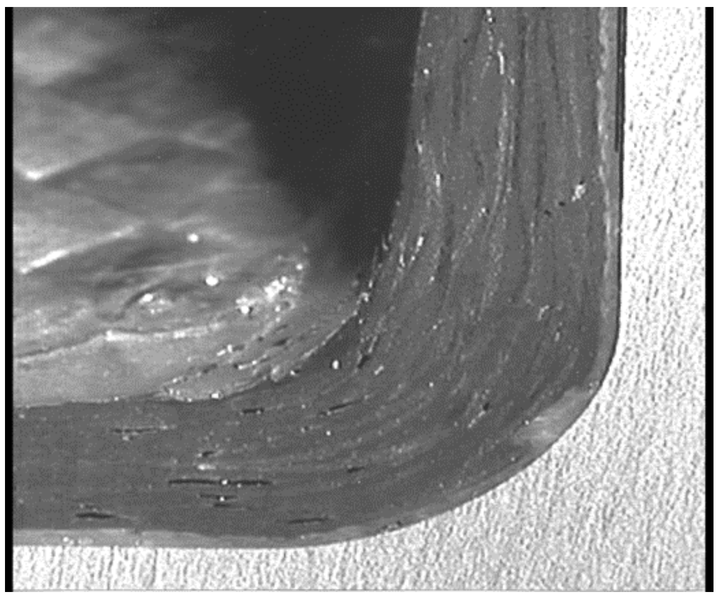

Figure 47. Porosity of a prepreg carbon composite in a corner of a part

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15.5.2 Out of autoclave prepregs

While new technologies share some complexities in design for manufacturing, they maintain a competitive advantage if they eliminate the need for an AC, such as OoA prepregs. OoA prepregs are not without failings as they can struggle with microporosity and bubbles due to the reduced consolidation pressure (Gangloff, Cender, Eskizeybek, Simacek, & Advani, 2016; Centea & Hubert, 2013). This does not mean OoA prepregs cannot reach the required performance as Toray BT250E-6 parts can show < 1% porosity, (Dorworth, 2021) although it has been shown OoA prepregs can have a propensity for voids. Further, the use of an AC only increases the fiber volume fraction by a few percent (Cender, Gangloff, Simacek, & Advani, 2014; Mortimer, Smith, & Olk, 2010).

Figure 48 shows a comparison of the Hexcel AC prepreg and OoA prepreg. Solvay MTM45 shows similar performance to prepregs (Figure 49) but does show that significant degradation can occur if the OoA prepreg is not used quickly. The loss of performance in shear strength is presumed to be the loss of tackiness of the OoA prepreg. There can also be significant amounts of porosity if the OoA is used after an extended out-life (Sutter, et al., 2010).

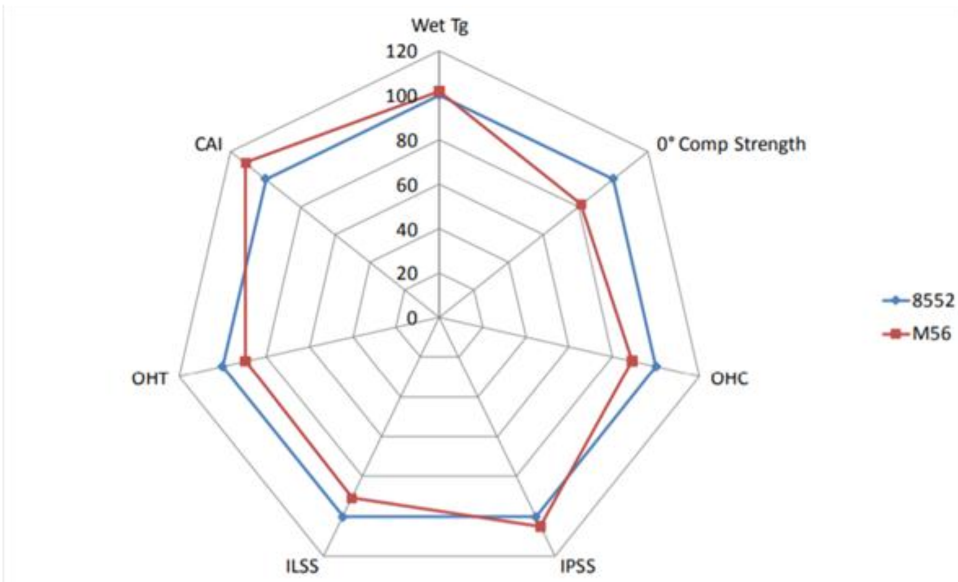

Figure 48. Comparison of Hexcel AC prepreg (8552) and OoA prepreg (M56)

Reproduced with permission from Hexcel

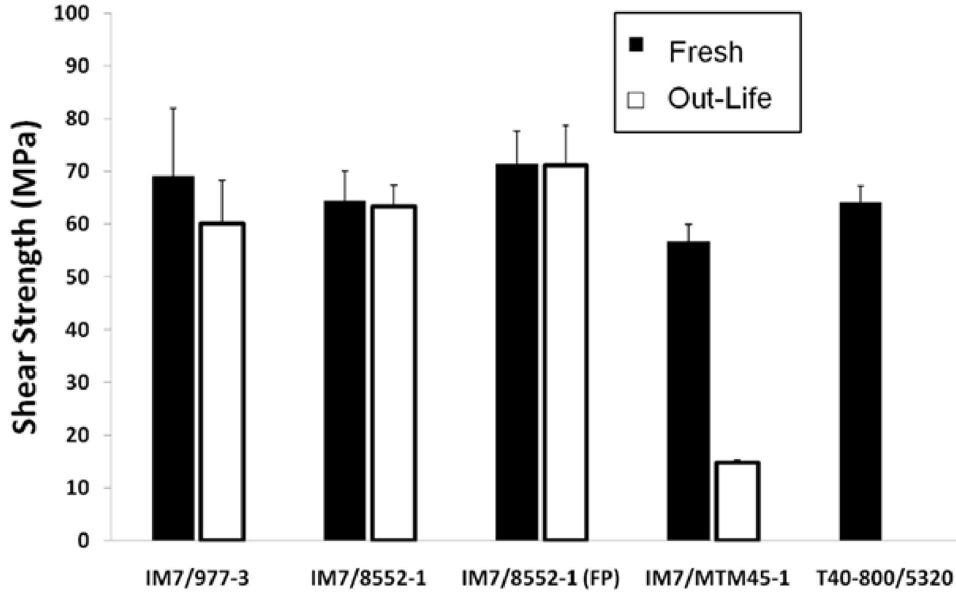

Figure 5. Short Beam Shear (SBS) Comparison

Figure 49. Comparison of shear strength for Solvay MTM45 OoA prepreg after 35 days of out-life

Reproduced from Fikes et al.

15.6 Published advantages of Z-pinning of prepregs

Z-pinning of prepregs is a direct competitor to stitched resin-infused parts for structures requiring increased out of-plane performance. They are an old technology but are still relevant and being studied. Dry fabrics have several techniques for through-the-thickness reinforcement, while prepregs only have z-pins (Liao, et al., 2021; Knopp & Scharr, 2021; Mouritz, 2020). Through-the-thickness reinforcement helps to increase damage tolerance, delamination resistance, joint strength, and post-impact properties (Gardiner G. , 2020d). Figure 50 shows Z-pins can have higher G_{Ic} than other though-the-thickness techniques, up to a 1,400% increase. A flying example of Z-pin usage is in the F/A-18E/F Super Hornet air inlet ducts, where Z-pins replaced titanium fasteners to save weight (37 lbs./plane), money ($83,000/plane), and had 70% lower costs than drilling and installing the titanium fasteners (Mouritz, 2007).

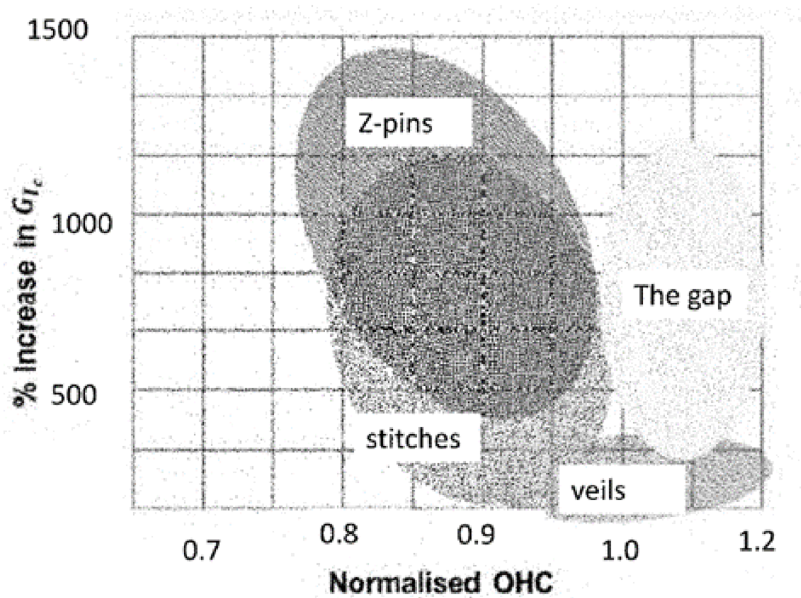

Figure 50. Ashy plot showing open hole compression and % increase in GIc for z-pins, stitching, and veils

Reproduced from patent US20190322057A1

https://patents.google.com/patent/US20190322057A1/en?oq=US+2019%2F0322057

15.7 Published disadvantages of Z-pinning of prepregs

Z-pins can have many advantages, especially when prepreg is required; but, like any technology, Z-pins have undesired consequences. First, as previously stated, Z-pins are only used for prepregs, they cannot be used for infused parts because there is no resin to hold the Z-pins in place. Second, and more importantly, Z-pins degrade the in-plane properties more significantly than other through-the-thickness reinforcements, such as braiding and stitching (Mouritz & Cox, 2000). Some of these properties are elastic modulus, strength, and fatigue. Further, adding more Z-pins increases the out-of-plane performance while monotonically decreasing the in-plane performance (Mouritz, 2007). Adding more Z-pins can also significantly decrease the fiber volume fraction, up to 10-15% decrease in fiber volume fraction with only one to two volume percent of Z-pins. The Z-pins can cause swelling of the prepreg, preventing full consolidation of the composite part, and increasing the resin content (Mouritz & Cox, 2010). Z-pins can also cause resin-rich regions due to fabric crimping (deforming into the Z-axis) and/or the fabric distorting around the Z-pin, making a source of microcracks (Mouritz, 2007), see Figure 51. Additionally, Z-pins can be difficult to administer.

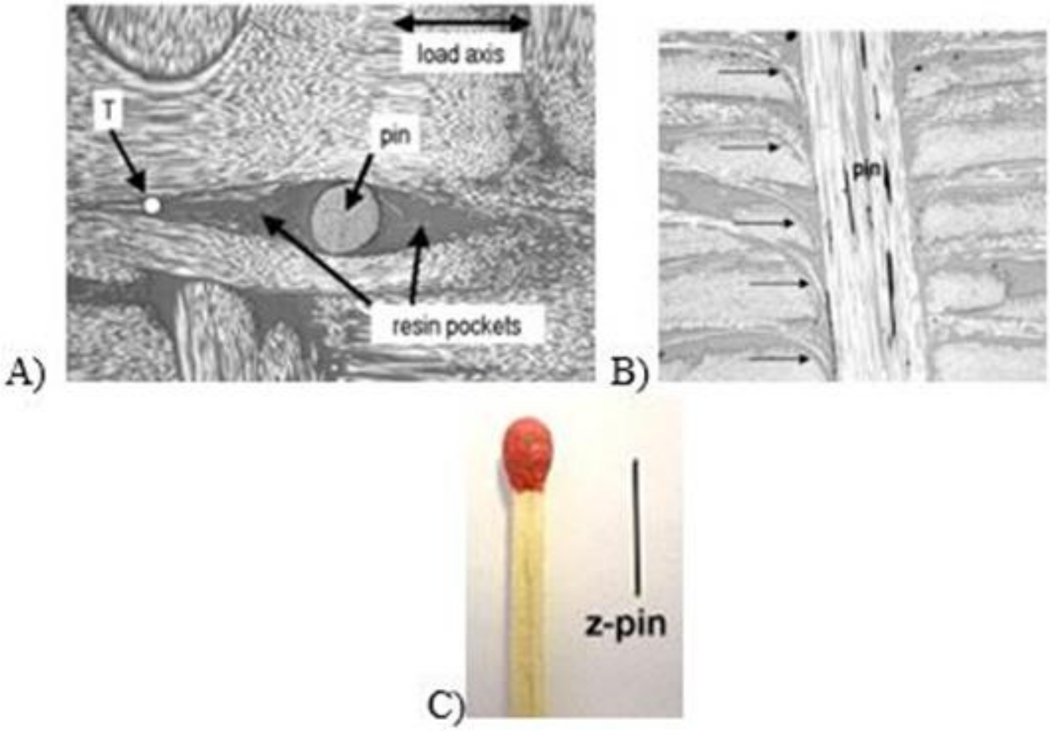

Figure 51. Resin pockets and crimping with Z-pins
A) Image of a resin pocket due to fiber distortion
B) Crimping of fibers through the Z-axis after adding Z-pin
C) Image of Z-pin with match for size comparison
Reproduced from Mouritz et al.

15.8 Published advantages of infusion

Resin infusion has been called the “technology with the most potential” by the CEO of the National Composite Center in Bristol, England. Therefore, due to the potential and the advantages, resin infusion is very likely the next step in technology for aerospace. Also, the overall process must be considered, not solely a comparison of raw materials, manufacturing costs, etc. Often, a streamlining of the manufacturing process, lower raw material costs, and less assembly can all equal a significantly lower tact time and/or cost (CompositesWorld, 2019a).

15.8.1 Unitized structures

One of the main advantages of resin-infused parts is the ability to make complicated, unitized structures. A complex prepreg part is made of several parts that are either cured independently and joined, co-cured, co-bonded, or mechanically fastened (Gardiner G. , 2016d; CompositesWorld, 2019a). Eliminating significant amounts of fasteners (NASA claims up to

80,000 fasteners in an aluminum wing) by unitization can decrease weight of the structure, improve performance, and lower costs (NASA, n.d.). An example is a Lockheed Martin Space Systems Trident II D5 missile that used a VARTM process to lower costs by 75% by reducing the 61-part count to one and then removing 376 fasteners, all of which are stress concentrations 101, 106 193. Another example for the F-35 was 3-D braiding was able to save 79 lbs., $200,000, and 95% of fasteners (Budwal, Kasper, Goering, & Ward, 2020; Mahfuz, Majumdar, Saha, Shamery, & Jeelani, 2004). A contemporary example with the aim of commercialization is MTorres, a machine solution provider that has been working on resin infusion for many years (see Wing of Tomorrow section); they are well on their way to completing this in the C-295 integrated wing skins and spars. A flying example is the Airbus A320 multi-spar flap that was able to integrate 26 separate pieces into a single piece using RTM. Integration can be pushed further with stitching of the dry fabric preform as large-scale preforms can be unitized (Gardiner G. , 2021c; Gardiner G. , 2015b). Ultimately, these integrated structures and the ability for complex shapes allow VARTM processes to produce more aerodynamic structures (Solvay, 2019).

15.8.2 Economics of infusion

The previous sections about the advantages of resin infusion highlight specific examples of unitization (up to 98% few parts) and lower manufacturing costs. This section will continue to show data related to the economics of resin infusion processes compared to other technologies.

15.8.3 VARTM costs vs thermoplastic vs aluminum

The Boeing RAPM project has already been discussed previously. This project demonstrated that for the parts being tested using several RTM processes (LP-RTM and C-RTM), a resin infusion process can be significantly lower in recurrent costs compared to prepregs and additive manufactured parts (Gardiner G. , 2020d).

15.8.4 Advanced Composites Technology (ACT) Program

Stitched resin-infused composites were able to demonstrate that they can be more economical for large assemblies than aluminum (Table 18) with approximately a 20% decrease in cost (Tenney, Davis Jr., Pipes, & Johnston, 2009). Table 18 adapted from Tenney et al. (2009) shows the NASA ACT cost for aluminum and stitched resin-infused wing.

Table 18. NASA ACT cost for aluminum and stitched resin-infused wing

MDXX Cost Parameters (CY96 M$)	**Aluminum Wing Box Cost**	**Stitched Resin Infused Cost**
Structural Wing Box (300 ships)	$3.181	$2.557
Structural Wing Cover (300 ships)	$1.516	$1.160
Wing Substructure (300 ships)	$0.461	$0.429
Wing Assembly (300 ships)	$1.204	$0.968

Assorted other programs have shown the monetary advantage of resin infusion compared to metals. The Airbus A220 infused wing expects 20% lower maintenance costs (Gardiner G. , 2021c; Danobat, n.d.). The Boeing 747 bullnose landing gear door shows a 41% lower weight, 62% lower part count, and 69% decrease in part numbers. Often the claim for lower costs for infusion only includes the lower raw material costs. A quantitative metric for this is a 36% decrease in the cost of raw material cost per foot for VARTM processes compared to prepregs (AMTAS, 2003).

One last example is the COMDOR project where a demonstrator for a Boeing 787 or Airbus A350XWB passenger door was replaced with a resin-infused door produced with RTM. A first design was completed as a "black aluminum" part but then a second iteration was produced to save 30% in cost and weight compared to the black aluminum iteration. Also, the lead time was decreased by 50% (CompositesWorld, 2012; Davis & Bohon, 1992).

15.8.5 Speed of manufacturing

Aerospace has a goal to increase the manufacturing rate from the current rate (< 60 planes/month) to 100 or more. The AC has been identified as the main bottleneck for prepreg processing, something the composite community has identified and is trying to address with OoA prepreg (CompositesWorld, 2019a; Sloan, 2020). First, VARTM processes can make a near-net shape structure. These structures require less trimming of the infused part, reduce bonding, and ultimately reduce waste (Gardiner G. , 2016f; Mouritz & Cox, 2000; Solvay, 2019). Second, the fabric is dry and not tacky like prepregs, making it easier and quicker to lay the fabric (Gardiner G. , 2014). As an example, Hexcel HiTape®, meant for AFP, can be laid up to 110 lbs/hr, reach 60% fiber volume fraction and match the performance of prepregs. For large areas, like the A220 wing, the layup can be very fast because a dry fiber mat can be draped on the large structure (Hexcel Corporation, 2020; Gardiner G. , 2014). Automating the dry fiber layup and vacuum bag layup for a VARTM process was able to lower "cycle time … 58% compared to rolled fabric and pick-and-place of cut plies by 50%. Manufacturing costs were down 11.5% and 31%, respectively." Third, through unitization, the resin infusion process can be much faster than prepreg. A prepreg process requires assembly, gap checks, and shimming, sometimes with many iterations, until no gaps are left (Gardiner G. , 2020a; Mouritz & Cox, 2000; Solvay, 2019). The wing the for the Boeing 777x has a large wing skin that requires very tight tolerances, something that can be loosened with full determinant assembly, a process of unitization of composite structures. A unitized structure may have some spring back but will not need shimming between the unitized parts. A LP-RTM process lowered the number of layup pieces by ~ 60 % and the touch points by 90 %. These examples are the epitome of "total cost" calculations showing the value of resin infusion (CompositesWorld, 2019a). Fourth, although vacuum leaks during infusion are an issue, vacuum pre-infusion checks allow a quality step to be introduced to help reduce failed parts due to vacuum leaks. Fifth, the footprint of a manufacturing facility utilizing infusion processes to produce wing skins at appreciable rates (> 60) will be smaller than for a prepreg facility, an important economic driver as current prepreg facilities can meet the 100 aircraft/month rate but not economically (Sloan, 2020b).

15.8.6 Storage

Storage of prepregs is difficult because they require refrigeration to prevent curing of the prepreg and have a relatively short expiration date. Resin infusion processes separate the dry fabric and resin, eliminating the requirement for the fabric to be refrigerated, significantly increasing the shelf life/out-time of the dry fabric. The actual infusion is quite short, on the order of minutes or hours, greatly lowering the potential impact of exceeding out-time requirements for the resin. Also, novel two-part resins do not require refrigeration at all, eliminating the freezer.

15.9 Published disadvantages of infusion

15.9.1 Wetting of parts

The most repeated perceived issue with resin infusion is how to prevent dry spots and/or porosity. A low viscosity resin is required to faithfully prevent dry spots, sometimes lacking the toughness of prepregs (Sloan, 2018). Porosity can be caused by race tracking of the resin, inconsistent clamping force of the part, shearing of the dry fabric, and early gelling of the resin (Hexcel Corporation, 2020; González, Vilatela, Molina-Aldareguia, Lopes, & LLorca, 2017). It is hard to predict this, and it is highly sensitive to the preform cuts, layup, and the mold material and geometry. For example, Darcy's law for permeability as a single parameter is not the most appropriate for crimped fabrics. Also, the flow difference between tows is dictated by the external pressure and the capillary forces for the individual fibers, possibly causing porosity at each crimp (Zhou, Alms, & Advani, 2008). Any fraying of the fabric or loss of any tows can also cause race tracking (González, Vilatela, Molina-Aldareguia, Lopes, & LLorca, 2017). The total infusion can be slow due to the low driving force of atmospheric pressure -- methods have been adopted to address this (flow media, lower resin pot pressure, etc.). Uniform wetting is also an issue and was identified as a large challenge for the Irkut MC-21 (González, Vilatela, Molina-Aldareguia, Lopes, & LLorca, 2017; Gardiner G. , 2021c); Also, any parts with dry sports must be scrapped and cannot be re-worked (Mendikute, Baskaran, Mateos, Aretxabaleta, & Aurrekoetxea, 2018; Gardiner G. , 2014; Sloan, 2012).

15.9.2 Lower pressure behind the resin flow front

Another issue for VARTM processes is the loss of vacuum/compaction pressure behind the resin flow front during infusion and curing. Initially the part has vacuum applied but the vacuum drops behind the resin flow front, lowering the consolidation and increasing the resin volume content (González, Vilatela, Molina-Aldareguia, Lopes, & LLorca, 2017). Any small variations in part thickness can have a large impact on the final physical properties as stiffness and thickness have a cubed relationship. Processes, such as secondary bagging, can help prevent this issue.

15.9.3 Tooling

Tooling can be very expensive for resin-infused processes, more so for RTM processes as they use matched molds that can handle high pressures. Very complicated machining of current technology can help offset some of the increased costs for RTM tools, but this is not often true (CompositesWorld, 2019a; Hexcel Corporation, 2020). To further drive up the cost, the RTM tools and mandrels can be quite complex. These cost issues are lowered if the tool and mandrel can be amortized over many parts but this is a large issue for low-scale production (Gardiner G. , 2020d; Sloan, 2020). RTM does have better capability for higher production rates than VARTM processes, which is required to amortize the matched molds. Molds for the RTM process are also very heavy and will limit the size of the part able to be produced. A section about 3D printed tooling was included in this review to show the market may be able to address some of these costs. Faster layup and cure cycles need to be developed to lower the time on the tool (Crosse, 2019; Sloan, 2020b).

15.9.4 Simulation

Simulation and modeling of the resin flow are capable but still have areas for growth as seen in Figure 52 examples and scales. The infusion process is then often a trial-and-error process for complicated parts, making infusion development costly and slow (González, Vilatela, Molina-Aldareguia, Lopes, & LLorca, 2017).

Simulating the distortions of the part is also difficult. The distortion and spring back is due to a difference in the in-plane and out-of-plane coefficient of thermal expansion, cure shrinkage, cure gradients, and interaction between the mold and the part (Gardiner G. , 2014).

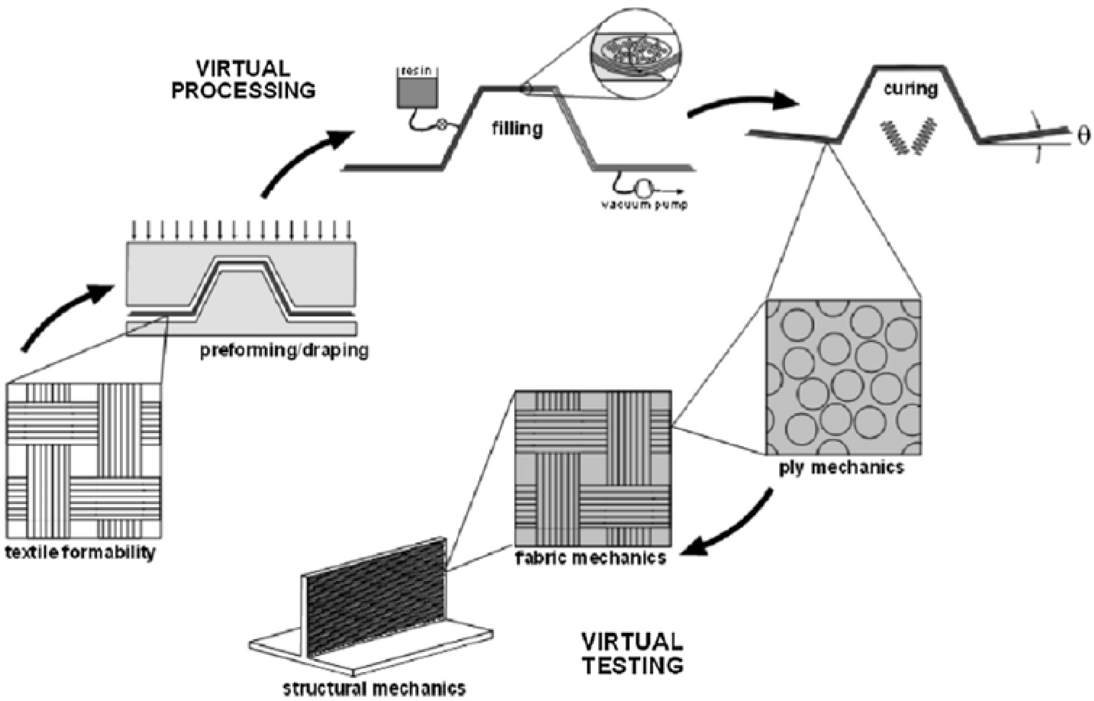

Fig. 9. Schematic of the multiscale modeling strategy for virtual testing and virtual processing of FRC.

Figure 52. Examples and scales for modeling resin infusion processes

Reproduced from Llorca

15.10 Stitched resin infusion

What follows is a short overview of the advantages, a description of microcracking, and mechanical observations about stitched resin infusion (SRI).

15.10.1 In-plane performance knockdown

Through-the-thickness stitching has been proven to increase many different properties of a specific laminate but there are also drawbacks as it reduces some of the in-plane properties of the laminate, nominally 10%.

15.10.2 Delamination

Laminate structures exhibit poor interlaminar fracture toughness and are susceptible to delamination when interlaminar stresses are presented. This could lead to a decrease of the structural integrity or failure. There are several different parameters that affect how well stitching improves a laminate: stitch density, stitch pitch, linear thread density, stitch speed, etc.

15.10.3 Damage initiation

Damage progression is one of the key advantages for stitched composites. Damage progression can be split in to three different stages: damage initiation, damage propagation, and final damage failure. Table 19, adapted from Ishikawa (2013), identifies the damage initiation and final fraction loads for composite thicknesses. The stitched samples exhibit a transition of the failure method from a delamination-dominated mode for unstitched laminates to a fiber fracture-dominated mode for densely stitched laminates.

The relationship between force and indentation displacement for stitched and unstitched composites is based on composite thickness. Elastic behavior can be shown between the first and second loading cycles with no signs of change in the slope of the load-displacement curves. In the third load cycle, the first noticeable slope change can be observed. Densely stitched composites have smooth curves during damage propagation; composite damage is gradual and delamination spread is stable and uniform. Moderately stitched specimens have irregularities with intermittent small load drops. Sudden damage growth and delamination propagation occur due to the fact that when stitches are closely spaced, stitches bridge delamination cracks effectively and act as efficient crack arrestors for delamination damage, thus preventing sudden delamination spread (Tan, Yoshimura, Watanabe, Iwahori, & Ishikawa, 2013).

Table 20, also adapted from Ishikawa (2013), shows stitch fiber volume fractions vs force. Increasing the stitch density and stitch thread thickness increases the final failure load (Table 19). Stitches are effective in suppressing delamination growth and eventually raises the final failure load. Stitched composites show a lower load for the initial failure, likely due to resin pockets that can act as stress concentration and crack initiation sites. The delamination damage for densely and moderately stitched composites is greater than for unstitched composites as seen in Figure 53 (Tan, Yoshimura, Watanabe, Iwahori, & Ishikawa, 2013).

Table 19. Damage initiation and final fraction loads for composite thicknesses

Type	**Damage Initiation Load (kN)**	**Final Failure Load (kN)**
Unstitched	2.86	13.4
200d6x6	2.68	14.1
500d6x6	2.60	14.4
200d3x3	2.40	16.1
500d3x3	2.14	17.2

Table 20. Stitch fiber volume fractions vs force

	Force (kN)	**Stitch Fiber Volume Fraction**
Damage Initiation Load	2.85	0
	2.68	0.087
	2.58	0.176
	2.38	0.353
	2.14	0.703
Final Failure Load	13.4	0
	14.2	0.087
	14.4	0.176
	16	0.353
	17.3	0.703

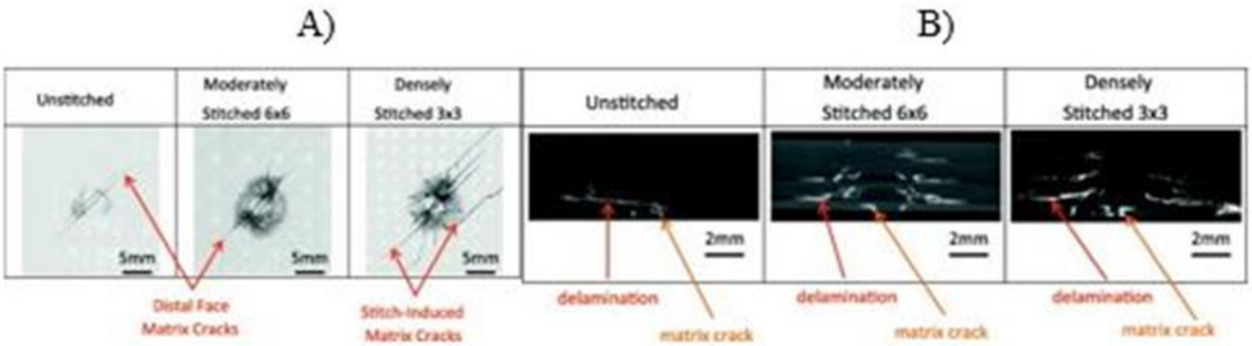

Figure 53. Damage for unstitched, and densely and moderately stitched composites
Delamination (A) and Matrix cracking (B)
for unstitched, moderately stitched, and densely stitched composites
Reproduced from Ishikawa

15.10.4 Damage propagation

Damage propagation is evidenced by delamination growth accompanied by matrix cracking. Figure 54A (Tan, Yoshimura, Watanabe, Iwahori, & Ishikawa, 2013) shows the delamination growth area for stitched and unstitched composites based on indention displacement; the red and yellow regions represent the delamination damage area. Increasing the indentation displacement increases the delamination size significantly more for unstitched systems. The densely stitched composites slow down the delamination growth as the indention displacement increases. Stitching will suppress delamination propagation using higher density and thicker stitches as seen in the microscopic final damage failure in Figure 55 (Tan, Yoshimura, Watanabe, Iwahori, & Ishikawa, 2013). The rate of delamination growth also decreases with indentation thread density and thread thickness.

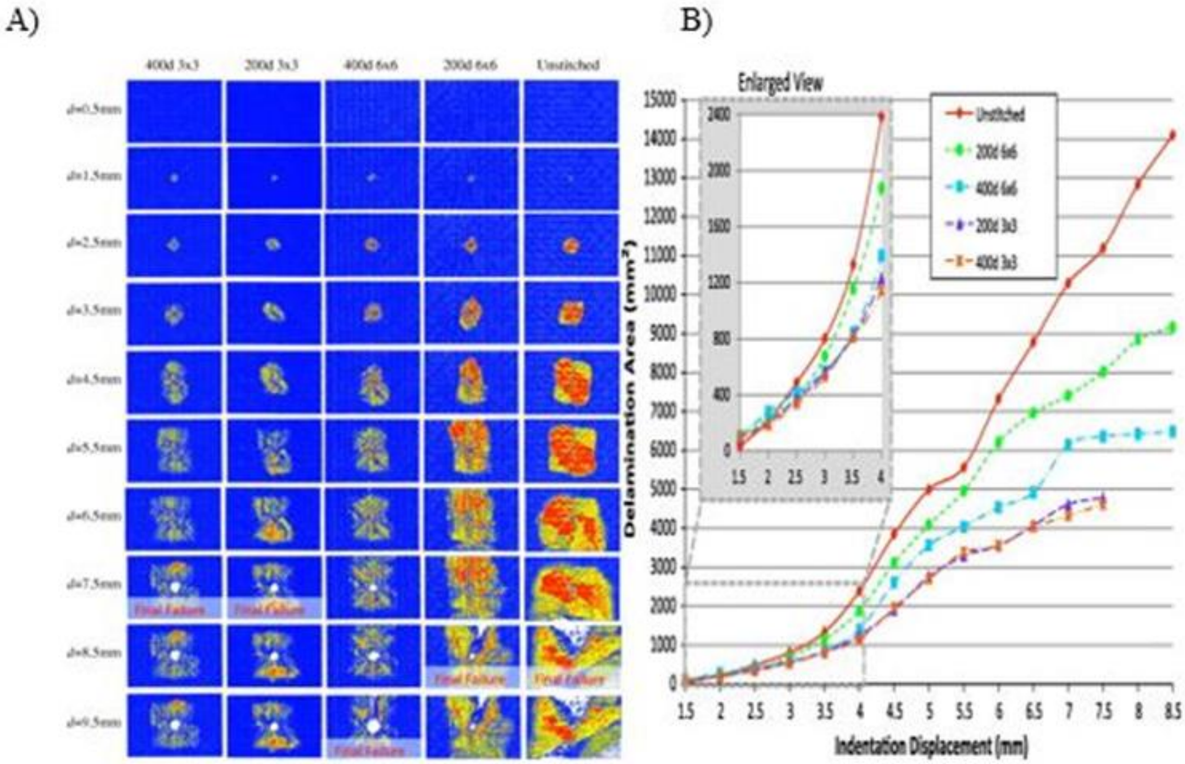

Figure 54. Delamination propagation based on indentation displacement

Red color indicates deeper displacement

Reproduced from Ishikawa

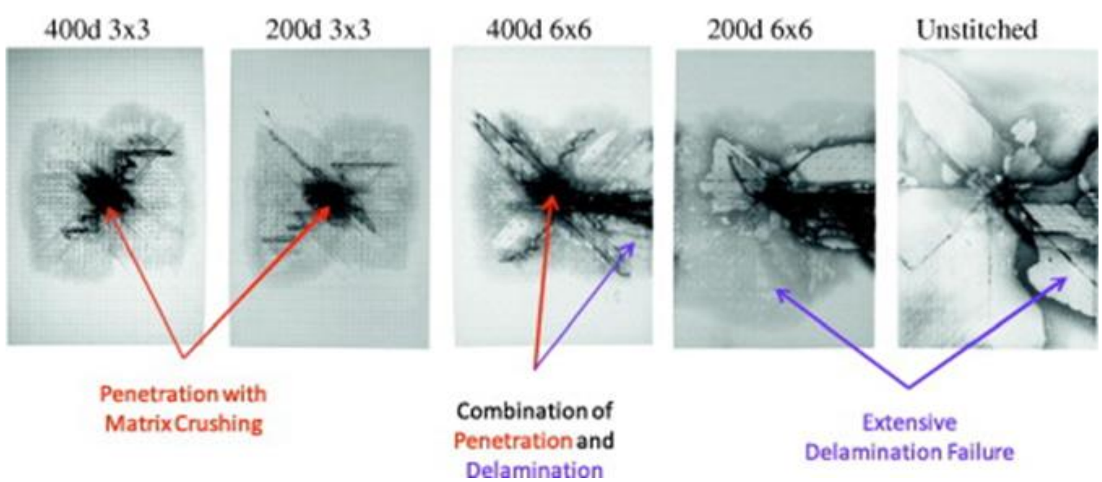

Figure 55. Microscopic final damage failure for stitched and unstitched composites

Reproduced from Ishikawa

15.10.5 Final damage failure

The final damage failure is the abrupt load drop upon reaching the maximum force in the load-displacement curve. Stitched composites have a higher final failure load, directly proportional to the stitch fiber volume fraction. Densely stitched composites fail at a higher maximum load, but the failure displacement is smaller than unstitched composites seen in Figure 56B.

Under low-velocity impact loading, the energy absorption is the same for composites that are stitched differently. Delamination, matrix cracks, and stitch debonding change with different stitch parameters. Densely stitched composites, during delamination propagation, absorb higher energy (Tan, Yoshimura, Watanabe, Iwahori, & Ishikawa, 2013).

The final failure is characterized by the penetration of the indenter resulting in matrix crushing with in-plane fiber fracture and stitch rupture as seen in Figure 56. The final failure mechanism for densely stitched composites is not extensive delamination propagation due to its high interlaminar strength provided by the stitch density. The composite structure is weakened due to the presence of delamination, therefore, a smaller delamination size results in a higher bending stiffness (Tan, Yoshimura, Watanabe, Iwahori, & Ishikawa, 2013). The load at the final failure of densely stitched composites is much higher than those of unstitched or moderately stitched composites.

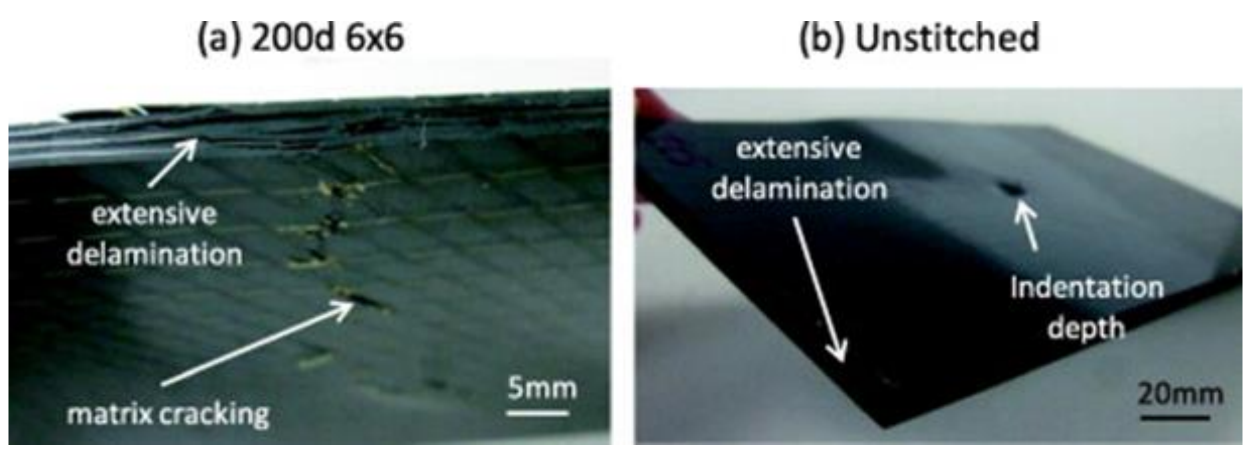

Figure 56. Final damage failure for stitched and unstitched composites
Reproduced from Ishikawa

15.11 Microcracking in composites

15.11.1 Microcracking of stitched composites

Microcracking is the formation of microscopic cracks that affect every form of composites. While microcracking in stitched and unstitiched composites are referred to as transverse microcracking, stitched composites are unique in microcracking occurs predominantly in resin-rich regions near the stitch (Liotier, Vautrin, & Beraud, 2011). Microcracking can occur when a resin-rich area formed during injection is subjected to any form of load -- this can happen in any type of laminate. There is uncertainty about microcrack propagation when dealing with stitched composites.

15.11.2 Microcracking in prepregs

Microcracks have long been an issue when dealing with any sort of composite material and prepregs are not immune to this. Microcracks are known to form and grow when composites are subject to any form of loading whether that be mechanical, thermal, moisture, etc. The life cycle of a composite can be simulated through the application of hygrothermal cycling (Gupta & Hojjati, 2019) (thermal and moisture cycles) and many observations can be made for a Cycom 5320-1 OoA prepreg investigated: voids begin around 100 thermal cycles and microcracks begin to occur after subsequent cycling. Voids could be the cause of the crack initiation during the thermal cycles as seen in Figure 57 (Gupta & Hojjati, 2019). During moisture testing, cycling saturation in water and then lowering the temperature showed increased microcracking than after thermal cycling alone. Combining moisture and thermal cycling can cause microcracks to form faster: the initial saturation and thermal cycling can cause microcracks, then further saturation can absorb more water in the current microcracks, and then expansion during cooling causes more microcracks. This process can be repeated to accelerate crack propagation (Gupta & Hojjati, 2019).

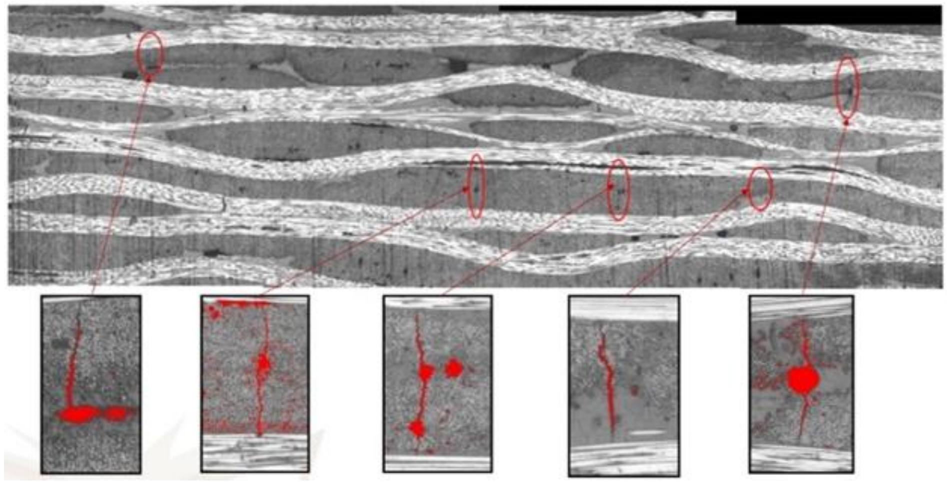

Figure 57. Microcracks near voids in prepreg composites after 100 thermal cycles

Reproduced from Gupta et al.

Increasing the number of thermal and moisture cycles performed on the prepreg composite increases the number of microcracks and reduces the average interlaminar shear strength at failure, see Figure 58 and Figure 59 (Gupta & Hojjati, 2019).

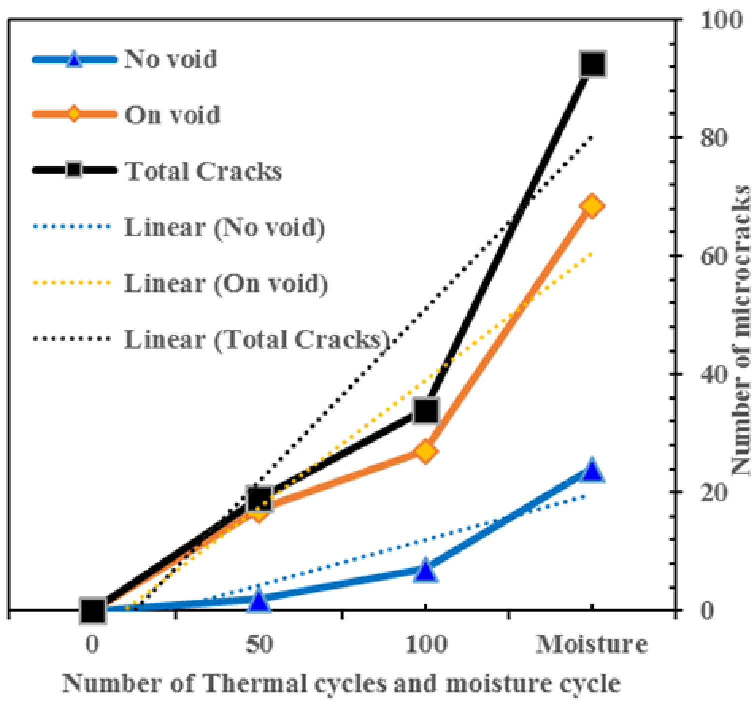

Figure 58. Number of microcracks with different treatments for a prepreg sample

Reproduced from Gupta et al.

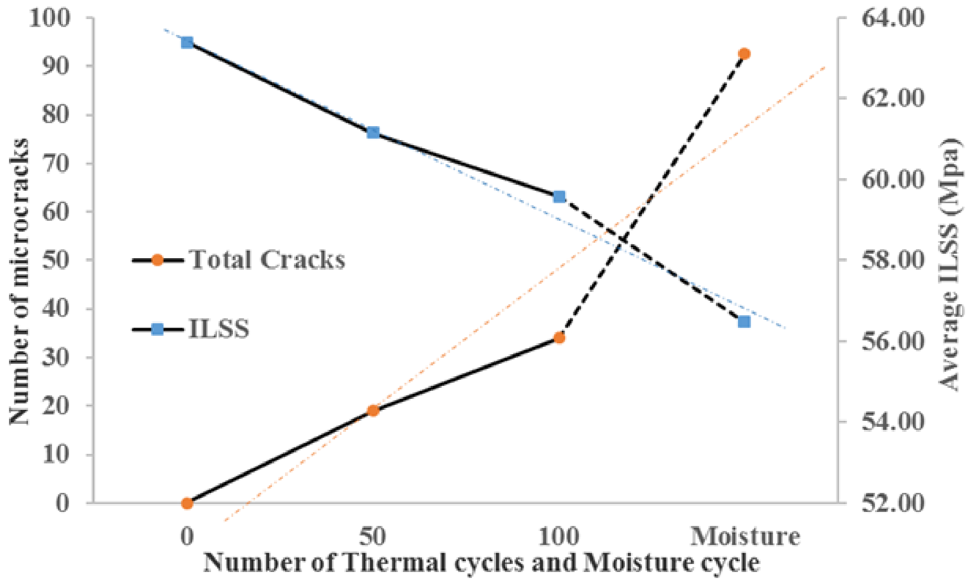

Figure 59. Comparison of microcrack amount and average ILSS after different processing conditions

Reproduced from Gupta et al.

Using nano X-ray CT, a composite sample was able to be measured before microcrack formation to help identify the root cause of microcracking as seen in Figure 60 (Kimura, Watanabe, Takeichi, & Niwa, 2019). It is believed that prepreg microcracking initiates at the interface between the reinforcement and the matrix through debonding and through small voids produced by plastic deformation.

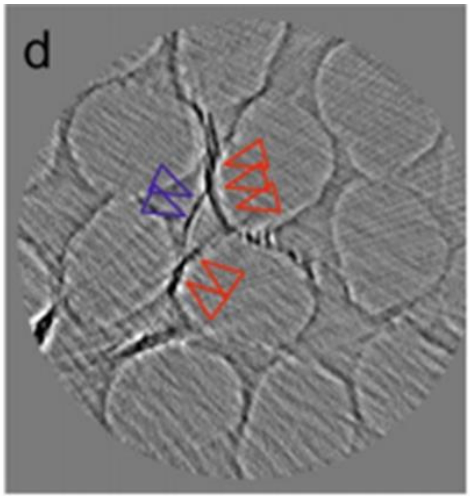

Figure 60. Nanoscopic X-ray computed tomography image along the axis of carbon fibers
Red triangles are matrix and fiber debonding and blue triangles are plastic deformation
Reproduced from Takeichi et al.

The presence of microcracks does not always reduce the mechanical performance of a prepreg sample (Timmerman, Hayes, & Seferis, 2003). Table 21, adapted from Timmerman et al. (2003), shows the microcracks for curing temperatures for epoxy/carbon fiber prepreg system. This table shows data for a cryo-treated epoxy/carbon composite sample cured at multiple different temperatures. Although the number of microcracks increased with higher cure temperature, it was stated no statistical difference was measured for flexural modulus, flexural stress at yield, or CTE for any of the samples cured at different temperatures. This shows microcracks can be present without detriment to some performance metrics. ILSS was not measured.

Table 21. Microcracks for curing temperatures for epoxy/carbon fiber prepreg system

Average Final Crack Density	**Cure Temperature °F**
10.1	158
10.3	176
23.2	212
25.9	248
34.4	284
33.8	320
34.1	356

15.11.3 Microcracking in non-crimp fabrics

Microcracking also occurs in non-crimp fabrics (NCF) as they employ structural stitching to bond the carbon fiber tows, different than reinforcing stitching. The NCF stitches binding the carbon tows may form resin pockets, may induce microcracking and shorten the composite's life cycle. A Hexcel NCF with Hexcel RTM6 resin was tested through a 2,000 hygrothermal cycles to simulate the life cycle. Two sample types were compared: an NCF sample with the stitching yarn removed and a NCF with no modification. The presence of humidity does not show any significant and detectable effect in the stitched non-crimp fabrics. NCF composites with stitching formed cracks earlier than the NCF samples with the stitching removed (Liotier, Vautrin, & Beraud, 2011).

The orientation of multi-ply laminates is a critical parameter in controlling crack density. During hygrothermal loading, lower temperature causes more microcracking than does elevated temperature. The type of yarn used for stitching also has a significant influence on the density of the microcracking, see Figure 66. Figure 61 (Liotier, Vautrin, & Beraud, 2011) shows the number of cycles for different materials vs the crack density for stitched samples after thermal cycling.

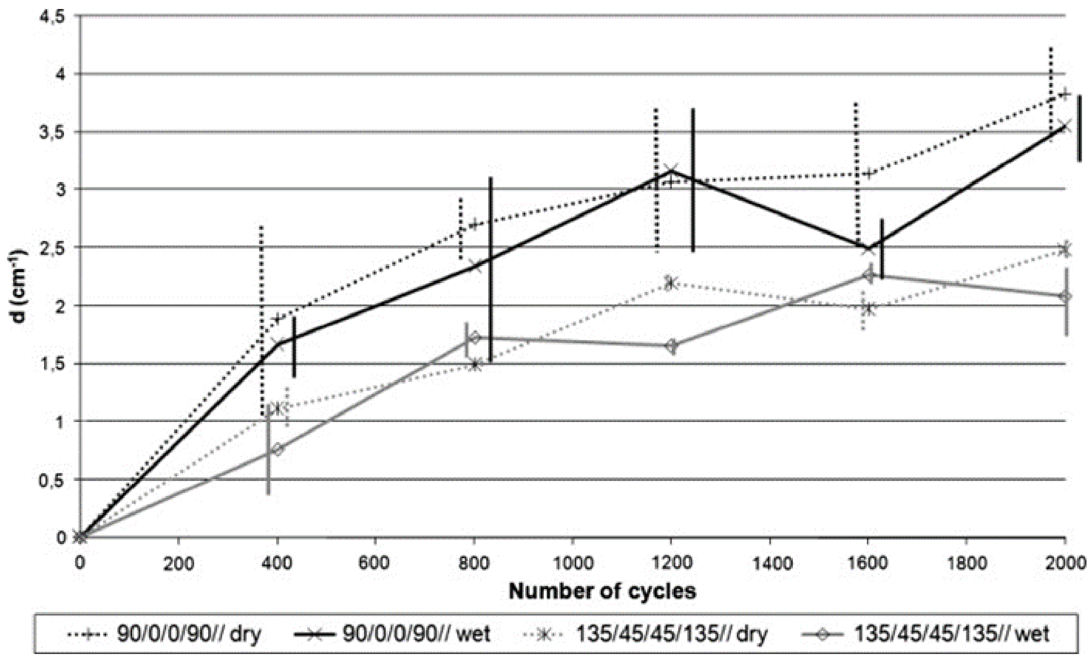

Figure 61. Number of cycles for different materials vs crack density for stitched samples after thermal cycling

Reproduced from Liotier et al.

15.12 Mechanical loading of stitched composites

Stitching has a strong effect on the failure mode of the composite structure. Below, the various failure modes are discussed individually.

15.12.1 Mode I

By incorporating through-the-thickness stitching, mode I fracture energy is increased and is dependent upon thread choice. The efficacy of stitching to increase the mode I fracture energy lowers as the delaminated front proceeds away from the stitch row (Drake, Sullivan, Lovejoy, Clay, & Jegley, 2021). Figure 62 shows the stitch density and linear thread density vs normalized Mode I fracture energy. An increase in the mode I normalized fracture energy can be obtained by increasing the stitch density (Figure 62A), stitch thickness, and stitching thread material (Figure 62B). Mode I fracture energy is controlled by the thread stiffness and stitch tensile strength. “A uniform distribution of untwisted filaments within the displaced region of in-plane fibers is developed, thereby decreasing the resin-rich pockets near the stitching regions” (Drake, Sullivan, Lovejoy, Clay, & Jegley, 2021).

Typically, an increase of linear thread density results in a reduction of the in-plane mechanical properties; however, untwisted carbon fiber threads within woven carbon fabric increases mode I interlaminar fracture energy without impacting in-plane properties. This may suggest that untwisted stitching threads may be able to increase the out-of-plane properties without sacrificing the in-plane properties (Table 24). The architecture of the twist can result in a slight decrease in the effective tensile modulus of the twisted fiber. The tensile strength can be increased significantly, however, by twisting the fiber. Stitching provides the same delamination resistance for in-plane fiber orientation (Drake, Sullivan, Lovejoy, Clay, & Jegley, 2021).

Table 22, reproduced from Dransfield et al. (Dransfield, Jain, & Mai, 1998), shows the flexural modulus and ModeI toughness for (un)stitched preforms.

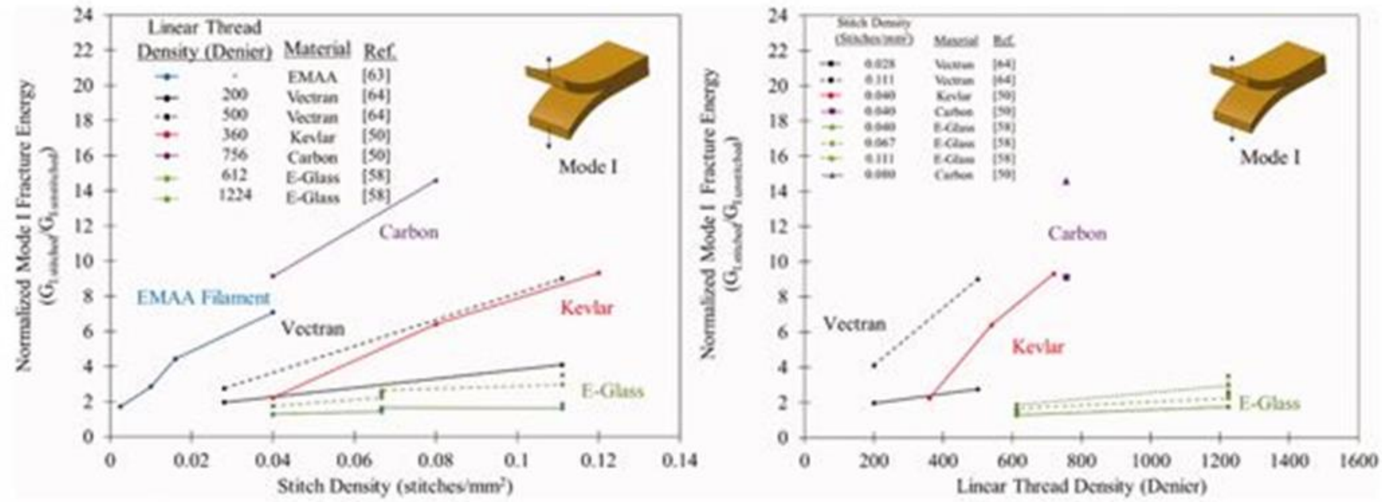

Figure 62. Stitch density and linear thread density vs normalized Mode I fracture energy

A) Stitch density vs normalized Mode I fracture energy for different stitch threads

B) Linear thread density vs normalized Mode I fracture energy for different stitch threads

Reproduced from Sullivan et al.

Table 22. Flexural modulus and Mode I toughness for stitched and unstitched preforms

Specimen	**Flexural Modulus E_f (Gpa)**	**G_{IRS} (kJ m^{-2})**	**Improvement Factor**
Unstitched (Untabbed)	-	0.41±0.02	-
Unstitched (Tabbed)	97.5±2.3	0.44±0.05	-
2-ply Kevar 4 stitches cm^{-2}	95.5±4.4	2.03±0.04	4.6
2-ply Kevar 4 stitches cm^{-2*}	92.3±2.4	0.98±0.09	2.2
2-ply Kevar 8 stitches cm^{-2}	88.9±1.5	2.82±0.09	6.4
2-ply Kevar 12 stitches cm^{-2}	87.5±2.7	4.10±0.25	9.3
3-ply Kevar 4 stitches cm^{-2}	90.7±3.7	2.59±0.11	5.9
4-ply Kevar 4 stitches cm^{-2}	89.5±4.5	2.90±0.12	6.6
4-ply Kevar 8 stitches cm^{-2}	85.6±2.1	4.54±0.10	10.3
T900 Carbon 4 stitches cm^{-2}	88.0±3.3	4.02±0.13	9.1
T900 Carbon 8 stitches cm^{-2}	87.4±3.9	6.42±0.05	14.6
*Discontinuous Stitch			

The stitching provides improvement in mode I delamination fracture toughness (Figure 63) due to the elastic stretching of the thread and bridging of the thread across the crack until the thread fails or is pulled out from the matrix. By adding discontinuous stitches to a specimen, the delamination toughness increases 2-3x and increases up to 5x with continuous stitches, as seen in Table 22. Figure 64 shows the displacement vs load for unstitched Composites and stitched composites (Dransfield, Jain, & Mai, 1998). For comparison, note the differences in the y-axis minimum and maximum values.

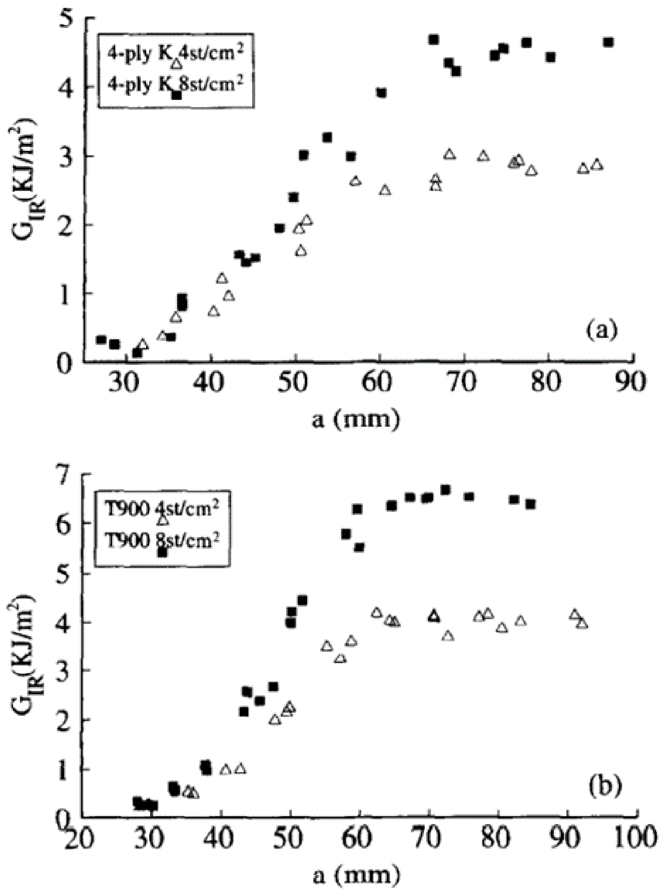

Figure 63. R-Curves for Kevlar and carbon threaded stitched composites
Reproduced from Dransfield et al.

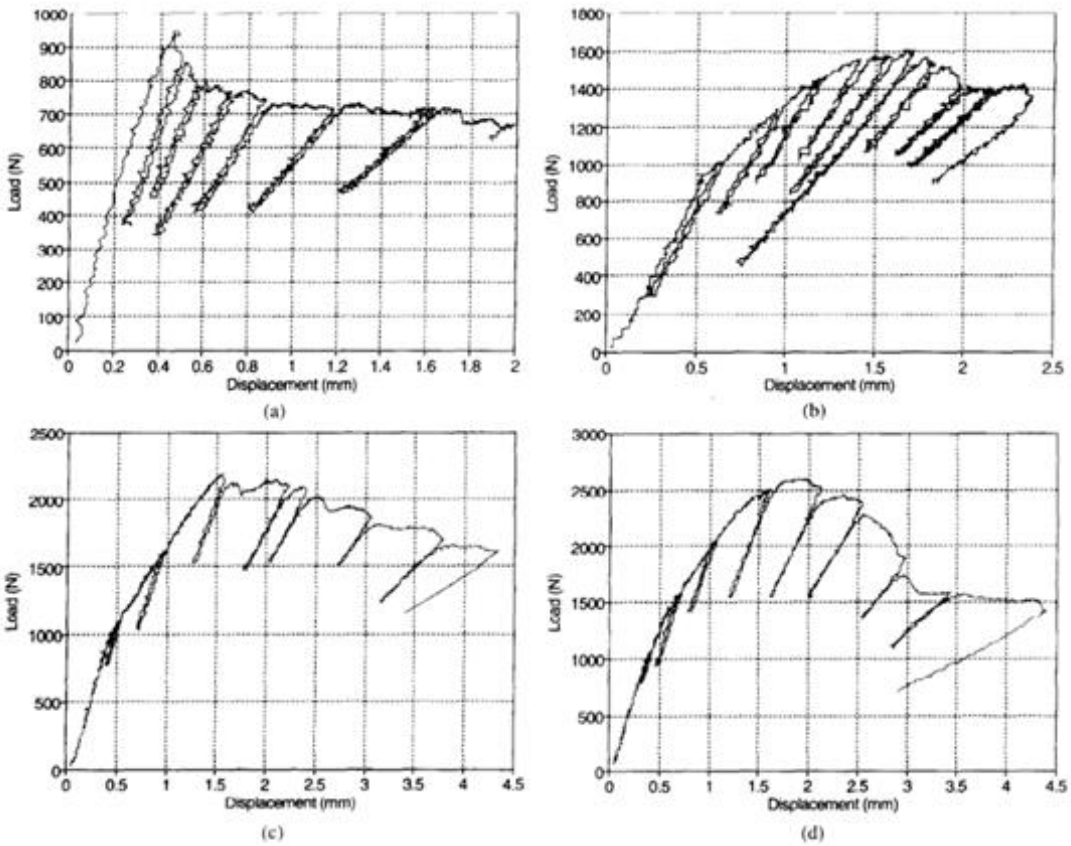

Figure 64. Displacement vs load

(a) Unstitched composites (b, c, d) Stitched composites

Reproduced from Mai et al.

15.12.2 Mode II

Stitches resist the crack front in a mode II delamination: an increase in stitch density increases the normalized mode II fracture energy (Figure 65), up to 330% when compared to unstitched composites, dependent on the fiber chosen. The thread material and the thread strength have an impact on the mode II fracture energy. The number of stitches along the crack front improves the mode II fracture energy but not for long crack growth with significant stitch bridging zone lengths. There is no blanket statement for stitching: higher linear thread densities for Kevlar increase the fracture energy but not for the polyester investigated (Drake, Sullivan, Lovejoy, Clay, & Jegley, 2021).

An increase in stitch pre-tension increases the mode II fracture energy. Due to a greater stitch pretension, there is larger surface traction (tangential forces to the surface) near the crack tip; this larger surface traction increases the mode II fracture energy at a greater rate (Drake, Sullivan, Lovejoy, Clay, & Jegley, 2021). An alteration of the orientation of through-the-thickness stitches can improve the steady-state fracture energy and stitches that are diagonally oriented provide the greatest improvement in mode II fracture energy. (Drake, Sullivan, Lovejoy, Clay, & Jegley, 2021)

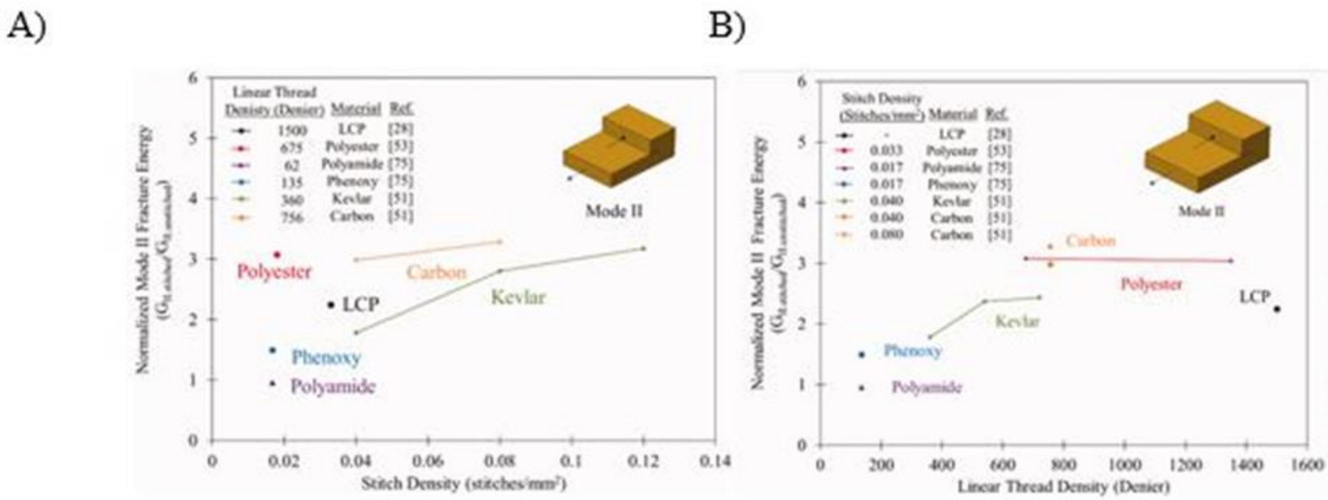

Figure 65. Normalized Mode II fracture energy

A) Stitch density B) Linear thread density

Reproduced from Sullivan et al.

The load vs. displacement curves for unstitched, Kevlar stitched, and carbon stitched samples is found in Figure 66 (Jain, Dransfield, & Mai, 1998). In unstitched specimens, when the load increases, the crack propagates to the central loading pin resulting in a sudden load drop (Figure 66 top left) . This occurs when the energy release rate exceeds the critical energy release rate. In stitched specimens, the crack growth is stable and there is an increase in crack propagation load with crack growth because of the development of bridging stitch thread zone. The delamination zone also increases for stitched specimens with a rising R-curve. A load drop can be noticed for stitched composites (the steps in Figure 66) that suddenly stop due to the crack approaching the next stitch; this is noticed more in low-stitch density specimens. The load process is continuously repeated until the crack reaches the central loading pin (Table 23). It is important to highlight the GIIRs, the steady-state toughness, value cannot be measured for the unstitched specimen as the crack propagation is uncontrolled.

Table 23, reproduced from Jain et al. (1998), shows Mode II delamination toughness for (un)stitched preforms.

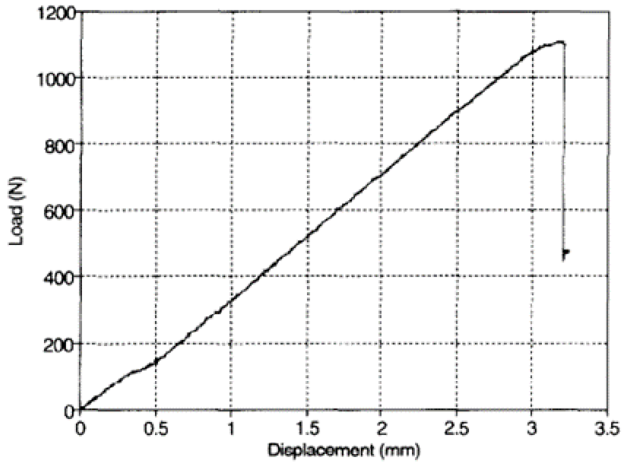

Fig. 3. The load vs displacement plot for an unstitched ENF specimen.

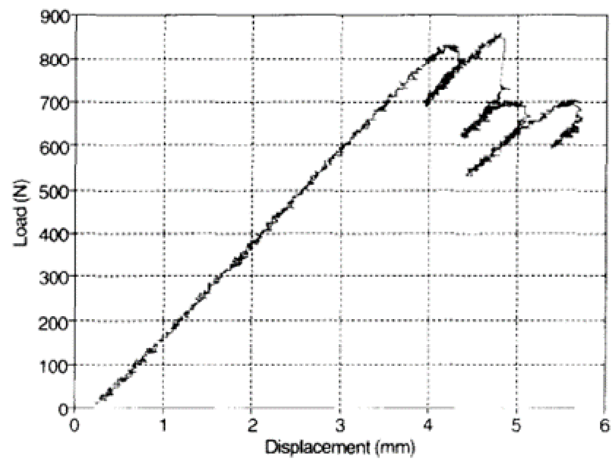

Fig. 4. The load vs displacement plot for an ENF specimen stitched with 2-ply Kevlar thread at 4 stitch cm^{-2}.

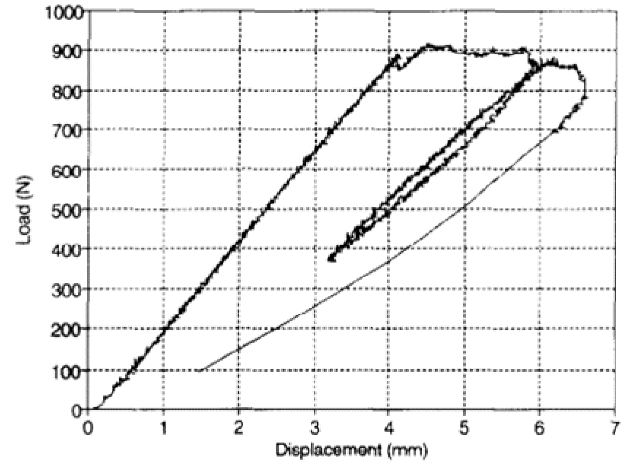

Fig. 5. The load vs displacement plot for an ENF specimen stitched with 2-ply Kevlar thread at 12 stitch cm^{-2}.

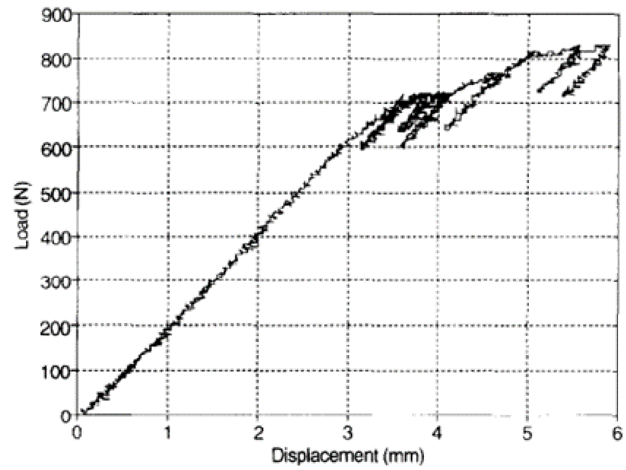

Fig. 6. The load vs displacement plot for an ENF specimen stitched with T900 thread at 4 stitch cm^{-2}.

Figure 66. Displacement vs load for unstitched and stitched composites

Reproduced from Mai et al.

Table 23. Mode II delamination toughness for stitched and unstitched preforms

Specimen	**Flexural Modulus E_f (Gpa)**	**G_{IRS} (kJ m^{-2})**	**Improvement Factor**
Unstitched (Untabbed)	-		-
Unstitched (Tabbed)	1.29±0.10		-
2-ply Kevar 4 stitches cm^{-2}	1.45±0.02	2.98±0.05	2.1
2-ply Kevar 4 stitches cm^{-2*}	1.50±0.05	2.30±0.05	1.8
2-ply Kevar 8 stitches cm^{-2}	1.51±0.09	3.62±0.03	2.8

Specimen	Flexural Modulus E_f (Gpa)	G_{IRS} (kJ m^{-2})	Improvement Factor
2-ply Kevar 12 stitches cm^{-2}	1.43±0.04	4.10±0.05	3.2
3-ply Kevar 4 stitches cm^{-2}	1.52±0.03	3.06±0.06	2.4
4-ply Kevar 4 stitches cm^{-2}	1.61±0.11	3.14±0.10	2.4
4-ply Kevar 8 stitches cm^{-2}	1.53±0.08	3.70±0.09	2.9
T900 Carbon 4 stitches cm^{-2}	1.42±0.03	3.85±0.08	3
T900 Carbon 8 stitches cm^{-2}		4.24±0.08	3.3
*Discontinuous Stitch			

15.12.3 Mixed mode

In a system that experiences multiple forces simultaneously, the modal ratio is defined as the mode I fracture energy divided by the mode II fracture energy. Figure 67 shows the constituent parts of the modal ratio for a stitched sample (Drake, Sullivan, Lovejoy, Clay, & Jegley, 2021). A stitch failure does not occur in a woven carbon/epoxy composite material system with a low modal ratio (<30%).

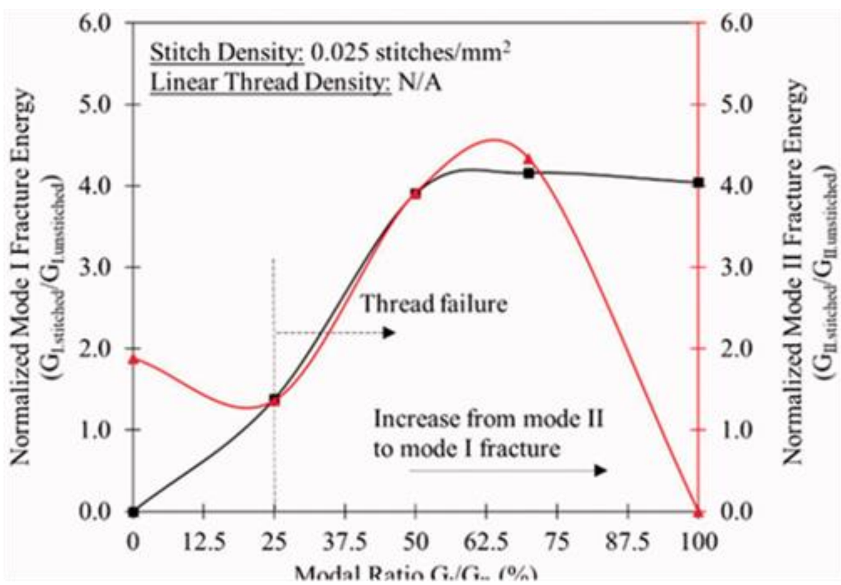

Figure 67. Modal ratio vs normalized mode I fracture energy

Black line is mode I and red line is mode II

Reproduced from Drake et al.

15.12.4 Interlaminar shear strength

Table 24, adapted from Drake et al. (2021), shows the positive correlation between stitch density and normalized interlaminar shear strength.

Table 24. Stitch density vs normalized interlaminar shear strength

Filament Count and Material	**Stitch Density (stitches/mm^2)**	**Normalized Interlaminar Shear Strength ($F_{stitched}/F_{unstitched}$)**
1K T300 Carbon	0.01	1.1
	0.04	1.27
	0.16	1.32
3K T300 Carbon	0.01	0.87
	0.04	1.07
	0.16	1.17

15.12.5 Impact load

During impact, laminates develop high interlaminar shear stresses due to local bending, causing large delamination regions and microcracking; mode II delamination occurs as a result. Delamination does not stop with through-the-thickness reinforcement, but the delamination area is reduced. The normalized damage area is independent of the impact energy for different stitch densities and linear thread densities for the low-impact energies measured, but the damage area is lower for stitched samples as seen in Figure 68(a) (Drake, Sullivan, Lovejoy, Clay, & Jegley, 2021).

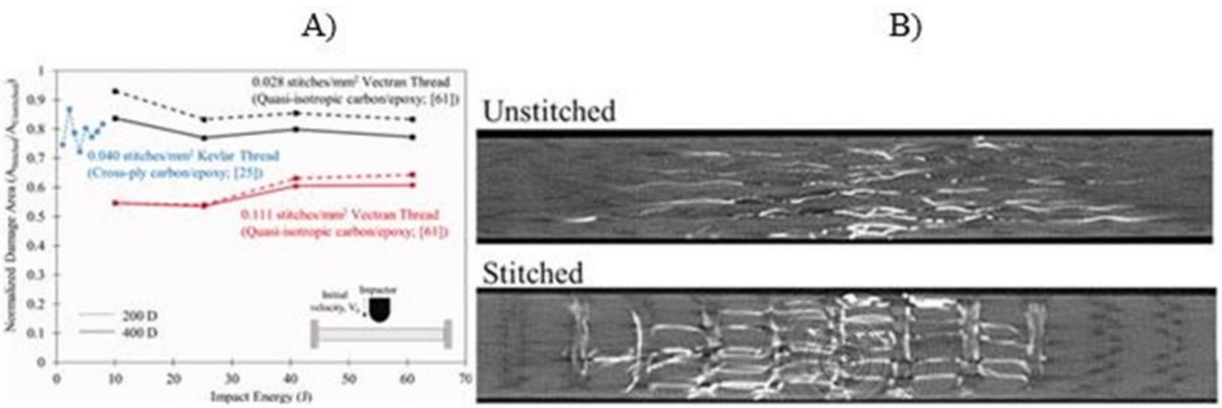

Figure 68. Impact load analysis

A) Impact energy vs normalized damage area

B) Delamination for unstitched and stitched composites after impact

Adapted from Drake et al.

Stitch density is the primary stitch parameter that arrests and delays delamination, leading to a decreased normalized delamination area. Changing the linear thread density, thread stiffness, thread pretension, or any other stitch parameter can lead to changes in the delamination area.

Delamination and microcracking can occur in the resin-rich areas around the stitching in the thickness direction. An increase in linear thread density increases the fiber waviness near the stitching and causes more microcracking and delamination. The formation of microcracks can n reduce fatigue life, increase the development of delamination associated with impact, and increase gas permeability during service.

15.12.6 Cryogenic loading

Stitched and unstitched composites have been subjected to cryogenic loading and the gas permeability of stitched composites with intermediate modulus (IE) carbon fiber specimens is lower than standard modulus (SE) carbon fiber specimens, see Figure 69. A single thermal cycle includes submersion in liquid nitrogen at -320 °F for ten minutes, removal from the liquid nitrogen, and then being held at room temperature for another ten minutes.

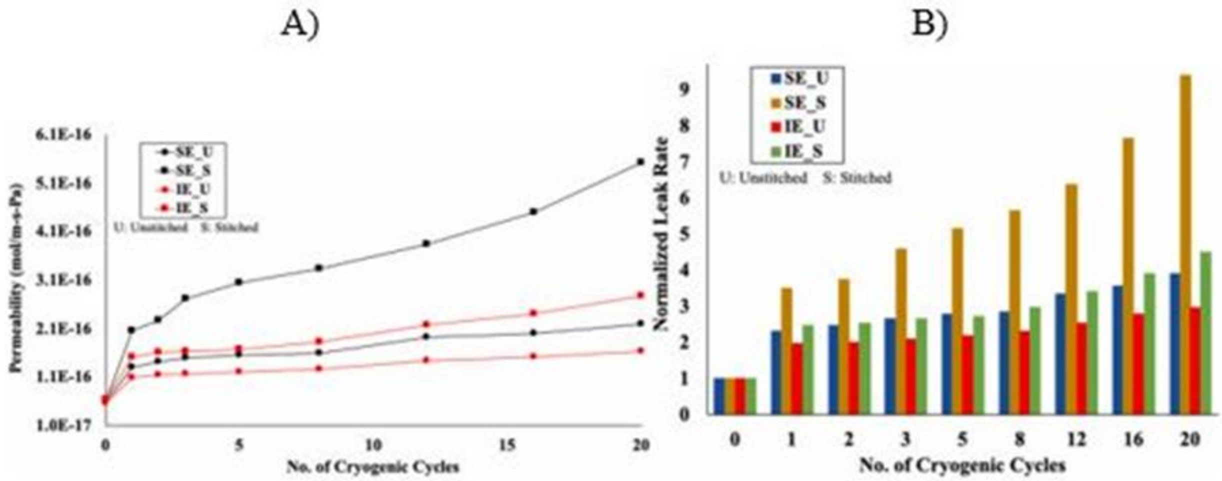

Figure 69. Cryogenic loading analysis

A) Change in permeability for stitched and unstitched laminates after cryogenic cycles

B) Normalized leak rate for stitched and unstitched laminates after cryogenic cycles

Reproduced from Drake et al.

Stitched specimens will generally have a higher microcrack density than unstitched specimens but a standard modulus unstitched composites can have equivalent microcrack density as a stitched intermediate modulus carbon fiber sample, see Figure 69(a). This suggests that a blanket statement that stitched composites have microcracks, while sometimes accurate, is slightly misleading as they can have a lower microcrack density than an unstitched sample. The microcrack density is greater in the middle of the composite than on the edge of the composite as shown in Figure 70 (Saha, Sullivan, & Baker, 2021). It is interesting to compare the amount of microcracking between the NCF fabrics and stitched composites as there are far fewer microcracks when dealing with through-the-thickness stitched specimens subjected to cryogenic loading than with NCF fabrics subjected to thermal loading (Saha, Sullivan, & Baker, 2021). This contradicts the statement made earlier in "non-crimp fabrics" that mentions the main cause of microcracks through thermal cycles is the lower temperature of the cycle, but also highlights that at least one cause of microcracking may be due to the difference in the coefficient of thermal expansion between the resin, reinforcement, and stitching threads, both non-structural weft stitching of NCF and of through-the-thickness stitching.

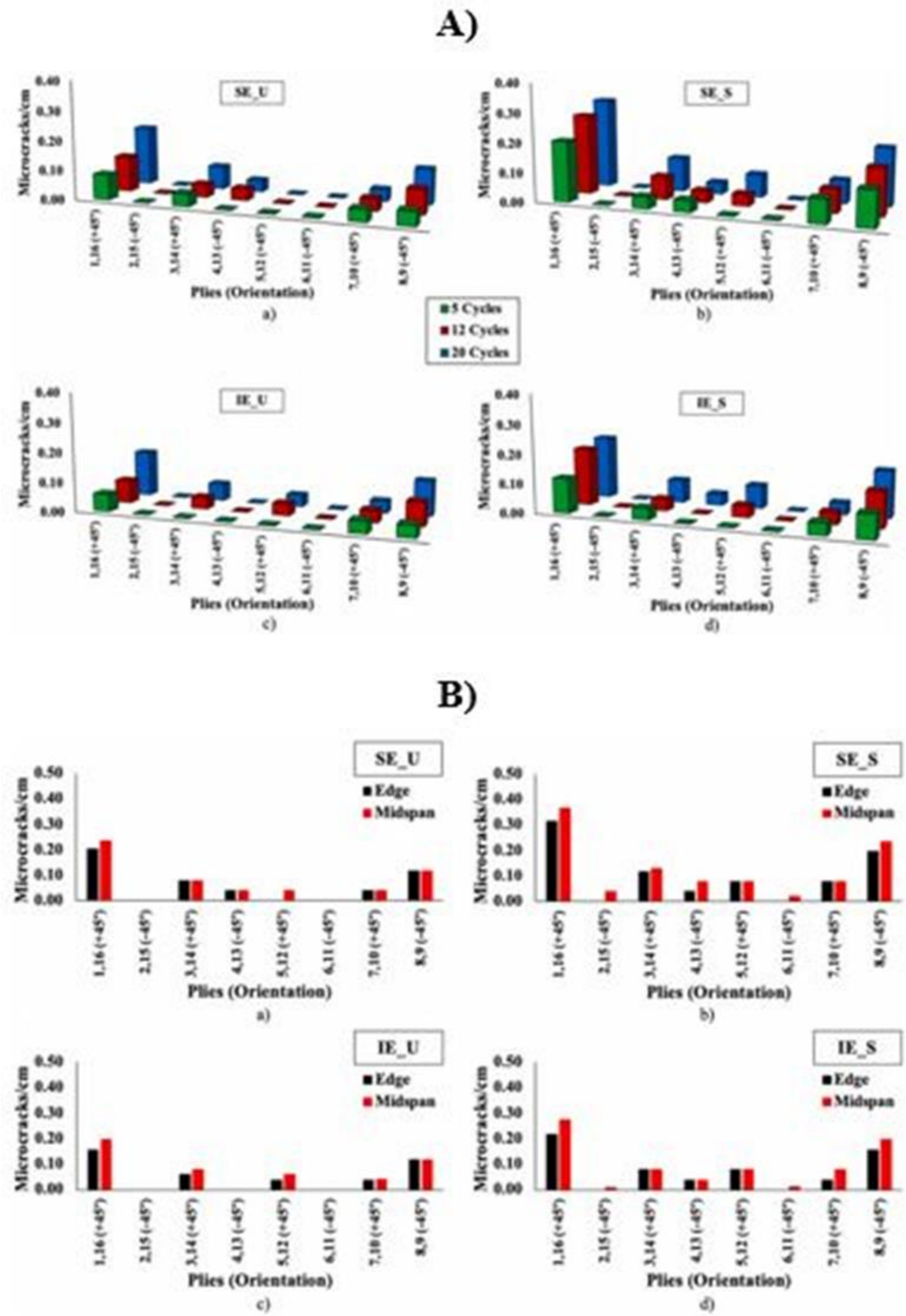

Figure 70. Ply orientation microcrack density

A) Ply orientation microcrack density for stitched and unstitched composites for different cryo-cycled counts (green = 5 cycles, red = 12 cycles, blue = 20 cycles)

B) Ply orientation and microcrack density for stitched and unstitched composites for the edge and midspan

Reproduced from Drake et al.

15.13 Stitching through sandwich composite

15.13.1 Observations

Through-the-thickness stitching is used for dry fabric preforms, it can also be used with foam core included. Stitching does not typically occur with honeycomb core materials as the open cells of the honeycomb could fill with resin, an issue mitigated by a closed-cell foam. Additionally, a needle can penetrate a foam, creating stitching that connects upper skin, lower skin, and foam with a though-the-thickness stitch.

Figure 72 shows the stitch density vs normalized fracture energy for linear thread density. An increase in stitch density results in an increase in maximum load before failure by 48% and a decrease in crack growth by 16% (Figure 72). An increase in linear thread density increases the maximum load at which stitch failure occurs and decreases the observed maximum crack lengths, but multiple stitch rows appear to fail for high linear thread densities. There are three failure mechanisms observed when dealing with very high stitched thread densities. These failure mechanisms are matrix-stitch frictional pullout at the face sheet-core interface, matrix-stitch column frictional pullout, and matrix-stitch frictional pullout with ductile core failure as seen in Figure 71 (Drake, Sullivan, Clay, & DuBien, 2021). "The failure of the stitch rows resulted in significant reductions in the fracture energies and produced unstable crack growth between the face sheet and the core." As the stitch densities increase, the calculated fracture energy increases as well (Drake, Sullivan, Clay, & DuBien, 2021).

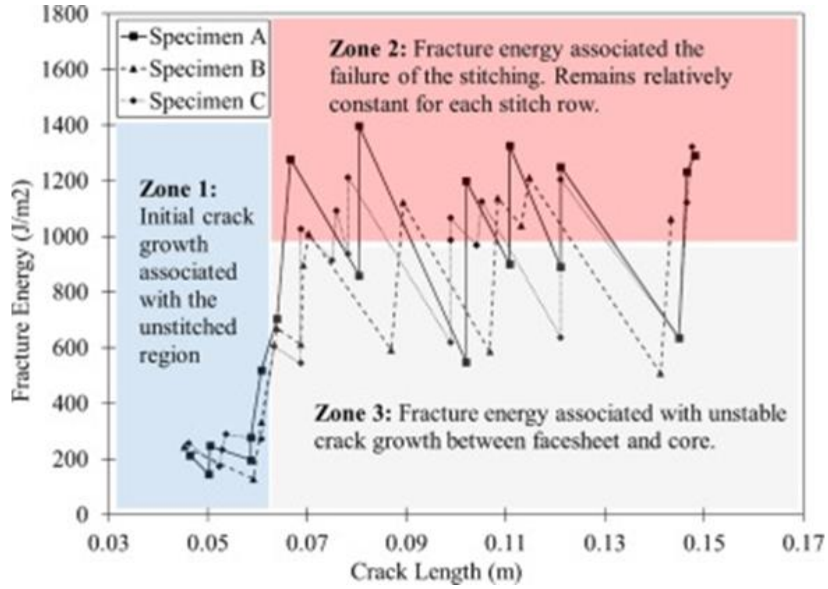

Figure 71. Crack length vs fracture energy for each failure mechanism

Reproduced from Drake et al.

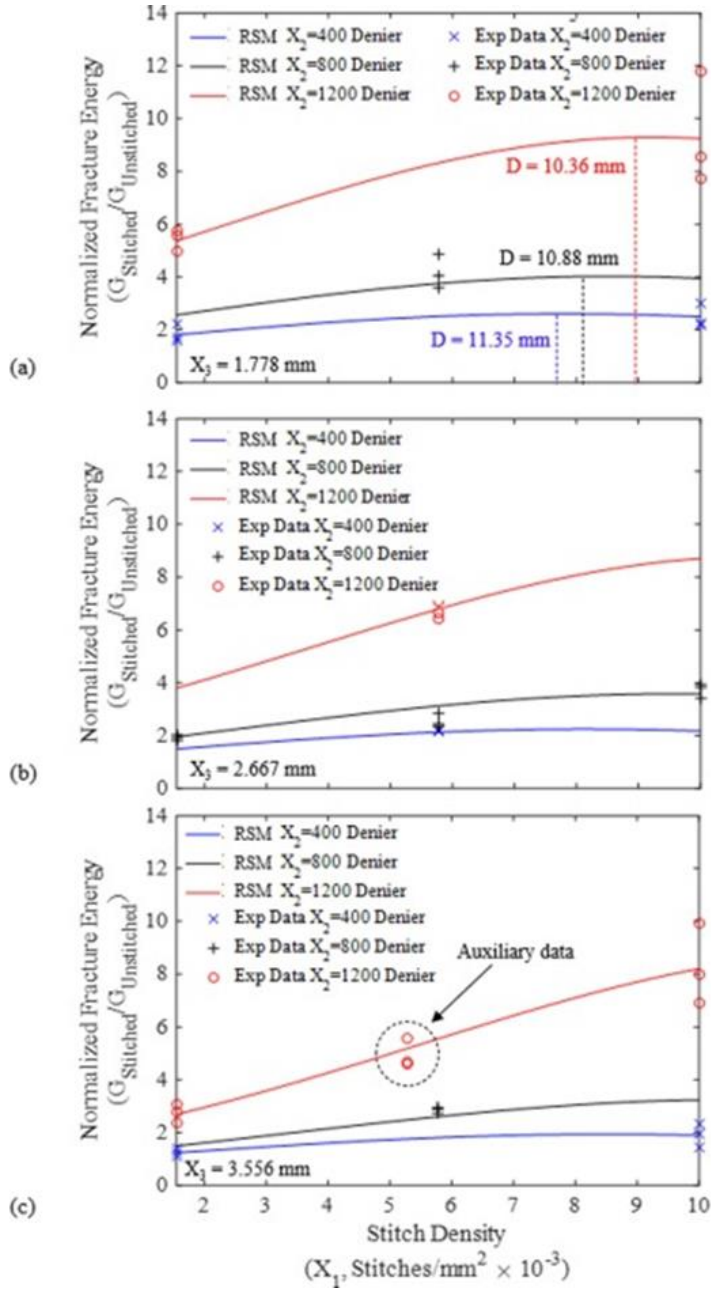

Figure 72. Stitch density vs normalized fracture energy for linear thread density
Reproduced from Drake et al.

As the linear thread density increases, the fracture energy significantly increases as well due to large-scale bridging. Also, an increase in the face sheet thickness decreases the normalized fracture energy. An increase in linear thread density also increases the normalized fracture density up to 400% (Figure 73), which was determined to be the most influential parameter. An increase in both the linear thread density and stitch density results in an increase in normalized fracture energy as seen in Figure 73 (Drake, Sullivan, Clay, & DuBien, 2021).

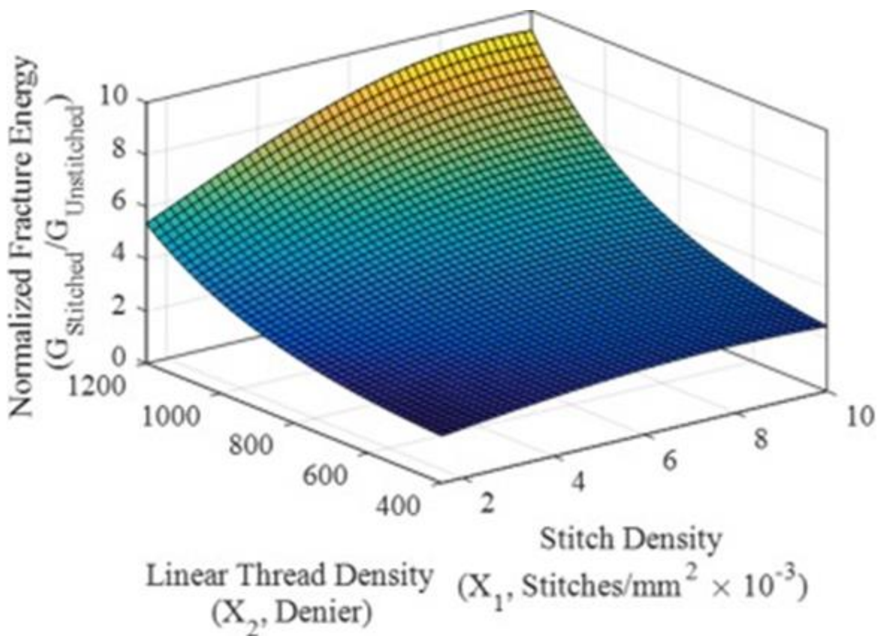

Figure 73. Linear thread density vs stitch density vs normalized fracture energy
Reproduced from Drake et al.

15.13.2 Advantages

Composites are very complex systems and adding stitching can even further complicate things. These parameters can range from stitch density, linear thread density, stitch material, stitch distribution, stitching style, and stitch pretension. There are many different advantages when deciding whether to stitch the sandwich preform. Stitching improves the mechanical properties while only adding a 1% weight increase. Also, a stitched sandwich composite has approximately 15% more flexural stiffness than its unstitched counterpart. An increase in stitch density also results in an increase in absorbed energy capacity and a reduced delamination area (Drake, Sullivan, Clay, & DuBien, 2021). Stitched composites still require development for specific applications as each variable can dramatically affect the performance of the system.

15.13.3 Disadvantages

When dealing with stitched sandwich composites, a few disadvantages can be observed. An increase of the stitch density will result in a lowered incipient impact failure load due to microcracks within resin-rich zones. Stitched composites can also have increased core cracking. The two primary failure mechanisms for stitched sandwich composites are stitch-column buckling and stitch-column penetration of the face sheet (Drake, Sullivan, Clay, & DuBien, 2021).

16 Conclusion

Resin infusion processes, both RTM and VARTM, will likely have an increased role in aerospace. They offer significant cost savings, increased performance, and higher production rates. Also, there has been much progress in resin infusion technologies that will allow higher automation, increased production rate, and higher reproducibility. As more research is conducted, both in academics and in industry, the current hurdles will be overcome, and the business case will grow for resin infusion. The only question is whether thermoplastics will progress faster than resin infusion and command more of the market share.

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