Design for manufacturability of a composite helicopter structure made by resin transfer moulding

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November 2007

A thesis submitted to McGill University in partial fulfilment of the requirements of the degree of Master of Engineering

Abstract

Resin transfer moulding (RTM) is a promising composite manufacturing method capable of producing high quality parts while meeting the rising demand for cost effectiveness. A collaborative research project involving academia, industry, and government in the Montreal area is under way to optimize RTM and help transfer this technology to local industries. As a technology demonstrator, the leading edge slat of the Bell 407 helicopter is being redesigned using composite materials and RTM. This thesis presents the mould design, part design for manufacturability, and actual production of half-length prototype parts. The mould and part designs were carried out concurrently taking into consideration results from stress analysis and flow modelling, as well as manufacturing constraints. A total of eight prototypes were manufactured. During the development of this project, important improvements were made in the way composite parts are manufactured by RTM. The lessons learned from this prototype design and manufacturing work will help to produce the full-size version of the slat as well as other components in the future.

Résumé

Le moulage par injection sur renfort (resin transfer moulding, RTM) est un procédé de fabrication prometteur, produisant des pièces en matériaux composites de haute qualité tout en ayant des coûts de production avantageux. Un projet de recherche incluant des collaborateurs du secteur académique, industriel, et gouvernemental dans la région de Montréal est en cours afin d'optimiser le procédé RTM et de faciliter le transfert de cette technologie aux industriels locaux. Pour démontrer cette technologie, le bec de bord d'attaque de l'hélicoptère Bell 407 est reconçu utilisant des matériaux composites fabriqué avec le procédé RTM. Cette thèse présente la conception du moule et de la pièce en fonction de la facilité de fabrication ainsi que de la production de prototypes demi-longueurs. Le moule et la pièce ont été conçus simultanément considérant les résultats des analyses de contraintes, d'écoulement de résine dans le renfort tout en tenant compte des contraintes pouvant être encourues lors de la fabrication. Huit prototypes demi-longueurs ont été fabriqués. L'expérience acquise lors de la conception et la fabrication du moule ainsi que des prototypes aideront à la production du bec de bord d'attaque pleine longueur en plus d'être utile lors de conceptions futures.

Acknowledgements

Support for "CRIAQ Project 1.15: Optimized Design of Composite Parts" is provided by Bell Helicopter Textron Canada, the National Research Council of Canada (Aerospace Manufacturing Technology Centre, Institute for Aerospace Research), Delastek Inc., McGill University, École Polytechnique de Montréal, the Natural Sciences and Engineering Research Council of Canada (NSERC), and the Consortium for Research and Innovation in Aerospace in Quebec (CRIAQ). The McGill Composite Materials and Structures Laboratory is a member of the Centre for Applied Research on Polymers and Composites (CREPEC). Funding was provided by NSERC through the postgraduate scholarship (PGS M) program.

Larry Lessard (McGill University) supervised this thesis and as such provided guidance throughout the project. Marc-André Octeau (National Research Council of Canada) provided considerable guidance and assistance in all aspects of the work presented in this thesis, and all composite manufacturing work was carried out using National Research Council facilities. Stéphane Héroux (Delastek) provided guidance with the mould design from a machining perspective, and all machining for this project was carried out by Delastek. Stress analysis for this project was carried out by France Thériault (McGill University) and flow modelling by Julien Feuvrier (École Polytechnique de Montréal). Steven Roy, Lolei Khoun, and Steven Phillips (McGill University) all actively participated in prototype manufacturing. Finally, Jonathan Laliberté provided guidance and assistance on many aspects of this work including composite part and mould design, solid modelling, and English to French translations.

Table of contents

List of tables

List of figures

Chapter 1 Introduction

Resin transfer moulding (RTM) is a promising technique for producing high quality composite parts at a comparatively low cost. Although the process has been under development over the last 30 years, it has yet to achieve its full potential in the aeronautical industry, particularly in Canada. As a result, a research project is being chaired by McGill University entitled "CRIAQ project 1.15: Optimized Design of Composite Parts". The purpose of the project is to integrate and optimize the various aspects of RTM part design to improve part quality and reduce costs. The project is a collaboration between a number of industrial, government, and academic partners in the Montreal area (Table 1.1).

Table 1.1: CRIAQ Project 1.15 partners

Organization	Contribution to project
McGill University	- Project curator - Part design - Stress analysis - Fatigue analysis - Optimization - Process modelling - Manufacturing - Mould design - Part testing
École Polytechnique de Montréal	- Flow modelling
National Research Council of Canada, Institute for Aerospace Research, Aerospace Manufacturing Technology Centre (AMTC)	- Manufacturing - Mould design
Delastek Inc.	- Mould fabrication
Bell Helicopter Textron Canada (BHTC)	- Project "client"

To demonstrate the technology being developed for this project, an aeronautical component is being designed and manufactured by RTM. This practical aspect of the project involves stress analysis, part design, mould design, process modelling, as well as the actual manufacturing of the part. The aeronautical component selected is the leading edge slat of a Bell 407 helicopter (Figure 1.1).

Figure 1.1: Bell 407 helicopter

The Bell 407 is a light, single engine, single rotor helicopter capable of carrying seven passengers [1]. The slat under consideration consists of an airfoil roughly 0.9 m (36") long with a chord length of 80 mm (3") located on the leading edge of the horizontal stabilizer. It is attached to the stabilizer with 4 evenly spaced brackets. The slat, brackets, and horizontal stabilizer are all currently made of aluminum alloys. The function of the slat is to improve the aerodynamics of the stabilizer at slow speeds and at high angles of attack [1].

For this project, a composite part is to be designed that will replace the aluminum slat and its four attaching brackets. The eight-fastener attachment to the horizontal stabilizer is to remain to allow interchangeability of the new composite slat with existing metallic slat assemblies. It is hoped that a number of advantages can be gained by using composite materials. First, part consolidation of the slat and four brackets into a single piece will reduce costs by simplifying installation and reducing the number of parts to be kept in inventory. Second, with a composite structure the material properties can be tailored to the application. In this case, the slat can be made more compliant to reduce stresses in the brackets.

RTM is a composite manufacturing method well suited to this component. It can produce a good surface finish which is important for aerodynamics. Also, it uses dry fabric which can conform to the complex shapes required for this part more readily than the pre-impregnated fabric required for autoclave processing.

This thesis focuses on the mould design, part design for manufacturability, and actual manufacturing of prototype parts. Despite continued advancements in RTM theory and understanding, adoption of the process by industry remains slow. This may be partly due to the challenges of mould design, the traditionally high up-front cost of producing a mould, and the continued difficulty in avoiding a time consuming and costly trial-and-error period at the start of production. The gap between academic advancements in RTM theory and practical applications in industry remains large. The goal here is therefore to contribute to the bridging of this gap, with a particular emphasis on the requirements for successfully producing real composite components in industry.

Chapter 2 Resin transfer moulding

2.1 Introduction to composite materials

A composite material is a macroscopic combination of distinct materials [2]. These occur naturally in cases such as wood and bone and have been fabricated by humans for thousands of years in cases such as mud bricks reinforced with straw. However, the term "composite" usually implies a "high performance composite" where high strength and stiffness fibres (discontinuous) are used to reinforce a matrix material (continuous). Traditionally, these composites are fibre reinforced plastic (FRP), however more exotic matrix materials such as metal, ceramic, and carbon are also possible.

Composite materials have gone from being nearly unheard of in the early twentieth century to being a significant contender for many engineering applications today. Fibreglass, Kevlar, and carbon fibre have become household words due to the proliferation of these materials in the sporting goods industry. However, it is the aerospace and aeronautical industries that continue to be at the leading edge of composite material technology.

When used properly, composites can offer many advantages over traditional materials. They can have higher strength-to-weight ratios and their mechanical properties can be tailored to a particular application. For example, a number of new helicopters use composite bearingless rotor flexbeams to connect the rotor blades to the rotor hub [3]. By using composites for this application, the flexbeams can be made strong enough to resist the applied shear and bending loads, axially stiff to resist centrifugal loads from blade rotation, yet flexible in torsion to allow pitch control of the blades. In complex structures, multiple parts can also be integrated into a single composite part. This is called part consolidation, or unitization, and can lead to substantial cost savings in assembly and inventory [4]. Finally, composites can have greater resistance to fatigue and environmental damage than metals [5]. These are simply a few of the potential benefits of using composites. However, it should be emphasized that achieving these benefits requires careful and proper implementation.

Not all applications will necessarily benefit from the use of composites. In a study conducted by NASA about lessons learned in the use of composites, it is cautioned that composites should only be used after careful study shows a clear benefit [6]. They go on to say that customers must have the infrastructure to inspect, maintain, and repair composites, an important consideration for the aeronautical industry. They also point out the issue of "black aluminum" designs. This is a term given to composite designs that simply duplicate the existing metallic design they are intended to replace. Although this may be appropriate in some situations, it will generally not be an acceptable design and, at the very least, will not take full advantage of the benefits of composites.

In the same NASA study [6], it is stated that cost is the "principal concern in the development, application and utilization of composites, and rightfully so". Composites will have to "buy their way" onto aircraft and weight savings alone no longer justify their use. That is, composites must be cost competitive with traditional metallic designs. Similarly, in a more recent study by NASA on the state-of-the-art in aerospace composite structures, cost was listed as one of the most significant barriers to the increased use of composite materials [7].

Both NASA papers indicate that manufacturing accounts for a large portion of the cost associated with a composite part. However, it was also noted that many past research and development programs have not addressed manufacturing technology. Traditional composites manufacturing techniques used in aerospace, particularly for high-performance components, require an autoclave. Operating an autoclave is expensive and often inefficient. As a result, there is a growing interest in out-of-autoclave manufacturing processes [8]. In light of this, both NASA papers list resin transfer moulding (RTM) as a promising manufacturing method for producing cost-effective composite components.

2.2 Introduction to resin transfer moulding

RTM is part of a class of composites manufacturing processes termed liquid composite moulding (LCM). LCM processes consist of a dry fibre preform placed within a mould cavity where resin is made to flow into the mould and "wet out" the fibres [9], [10], [11]. A great deal of variety is possible within this definition, including the rigidity of the tool, the method of inducing resin flow, the fibre and resin type, and the method for creating the preform (Table 2.1). Note that the nomenclature for these methods is often inconsistent in the literature and in some sources may differ from that shown here.

Table 2.1: Common liquid moulding processes

Process		Tooling	Description
RTM	Resin transfer moulding	Matched	Resin is injected into the preform under positive pressure.
ICM	Injection Compression Moulding	Matched	Similar to RTM but mould is only partially closed during injection and then fully closed after filling.
VARTM	Vacuum Assisted Resin Transfer Moulding	Single Sided	Resin is drawn into the preform by vacuum.
SCRIMP	Seeman's Composites Resin Infusion Moulding Process	Single Sided	VARTM with a patented distribution medium.
RIM	Reaction Injection Moulding	Matched	Reactive monomers are mixed and injected into a mould with no fibres. Polymerisation occurs during mould filling.
RRIM	Reinforced Reaction Injection Moulding	Matched	Similar to RIM but liquid includes low levels of chopped or milled reinforcements.
SRIM	Structural Reaction Injection Moulding	Matched	Similar to RIM but liquid is injected into a mould containing a fibre preform.

[12], [11], [13]

The term RTM will be used here to describe the process of injecting resin under positive pressure, with or without the assistance of a vacuum at the outlet, into a closed, rigid mould containing a dry preform. RTM is usually categorized as a low pressure process with the injection pressure normally less than 690 kPa (100 psi) [14].

Early work on advanced RTM in the aerospace sector is generally considered to have begun in the 1970s with more rapid development beginning in the 1980s.

However, variations of the RTM process appear to have existed as far back as the 1930s [15]. It also appears that in the 1950s, a small group of researchers had achieved what would today be considered state-of-the-art in aerospace RTM [16]. However, this knowledge was not passed on and had to be redeveloped years later.

Interest in RTM has grown over the years as a result of its many advantages [14], [15], [12]:

- dimensional and surface finish control
- ability to produce net or near net shape parts
- large, complex components, part integration, and tight radii can be achieved
- design can be tailored for good mechanical properties
- fibre volume fraction can be well controlled
- voids can generally be minimized or eliminated
- use of many reinforcement types and resin systems possible
- can have shorter overall cure cycles than prepreg processes
- high cost of prepreg material and storage avoided
- some automation possible to save labour
- low volatile emissions

Some of the disadvantages of the RTM process are as follows [14], [12]:

- mould design is critical
- mould filling can be difficult to control
- properties are not as good as vacuum bagging, pultrusion, or filament winding
- reinforcement can move during injection (fibre washout)

The many advantages of RTM clearly outweigh the disadvantages. For the correct application, RTM provides an excellent manufacturing option for producing composite parts.

2.3 The RTM process

The RTM process can be divided into four stages: preforming, mould filling, curing, and demoulding [17]. First, the dry fibre preform is made and placed in the mould. The mould is filled with liquid resin which is then solidified in the curing stage. Note that the curing stage actually begins as soon as the resin is mixed. However, usually the process is designed such that cure proceeds slowly until the mould has been filled. Once cured, the part is removed from the mould. In some cases, the part is demoulded before complete cure and post-cured in an oven. This can be a cost-effective way to improve throughput for high-volume production.

In addition, although RTM can in theory produce net-shape parts, a final post-machining or trimming step is often required [14]. In some cases, it is simply not worth the added complexity in mould design and filling strategy to produce a net-shape part [9]. A jig can be used to make this post-machining operation easier and more accurate [18].

Demoulding the part is generally straightforward provided appropriate measures have been taken. Careful surface preparation and the application of mould release agents are essential [18]. For high-volume production, compressed air or ejector pins can be used for automated demoulding [11]. The first three stages of RTM (preforming, mould filling, and curing) are more complex and will be discussed further in the following sections.

2.4 Preforming

RTM can be carried out with a wide variety of fibre types. In fact, there are no specific fibre types known to cause problems with RTM [15]. The most important manufacturing criteria for fibre selection is that the resin must naturally wet out the fibre.

The arrangement of dry fibres in the mould is called the preform. It can be made on a dedicated preforming tool or directly in the mould. If it is to be handled outside the mould, it must be made stiff enough to maintain its shape and fibre architecture. A number of methods borrowed from the textile industry exist to create three-dimensional shapes that can be handled. Binders or adhesives can also be used to hold the fibres together. However, in some cases this binder can have detrimental effects on the mechanical properties of the final part [9]. One of the potential cost-saving benefits of RTM is the possibility of automated preforming.

Preforming techniques can be divided into five categories [9]: cut and paste, spray-up, thermoforming, weft knitting, and braiding. Cut and paste is the simplest method and involves cutting shapes from the reinforcement and fitting them together with an adhesive or by stitching. It is the simplest technique in terms of equipment requirements but also the most manually intensive. Spray-up involves passing chopped fibre through a spray gun onto a preform tool. It can be highly automated but, as it uses chopped fibres, it is not applicable to high-end applications. Thermoforming involves clamping fabrics or mats in a preforming tool. It can also be automated but can produce only limited shapes and results in a higher level of scrap material. Weft knitting and braiding are textile techniques that are inherently automated but are the most demanding preforming options in terms of equipment requirements.

2.5 Mould filling

The mould filling stage consists of injecting resin into the closed mould containing the preform. There are three main types of injection strategies: point, edge, and peripheral [9]. The goal is to wetout all the reinforcement with no air pockets or voids. For high-volume production, it is also desirable for this to occur in as short a time as possible. Mould filling is considered to be the stage during which the most defects occur [9]. It is therefore one of the most carefully studied aspects of the RTM process.

To facilitate wetout of the reinforcement, resins are selected that can be injected with low viscosity. A maximum viscosity of 1 Pa·s (10 poise) is suggested by [15] and [9], and 0.5 Pa·s (500 cPs) by [14]. As a result, RTM has traditionally been carried out using thermosets. However, research is being carried out on liquid moulding reactive thermoplastic composites in which injections are carried out using monomer solutions which polymerize during processing [13].

2.5.1 Flow mechanisms

The flow of resin through the preform is governed by two mechanisms: bulk flow and fibre wetting [15]. Bulk flow occurs in the space between the fibre tows, whereas fibre wetting occurs within the fibre tows.

Fibre wetting occurs both radially to fill in the space within a fibre bundle from the sides and axially as resin moves along the fibre bundle. It can occur without external pressure by capillary action and also with the help of external pressure. Generally, full wet out occurs a few mm behind the bulk flow front [15]. However, since the wetting flow is less sensitive to applied pressure than bulk flow, it is possible for the wetting flow to precede the bulk flow at low flow rates.

Bulk flow is affected by three parameters: pressure gradient which is controlled by the injecting apparatus, viscosity which is a property of the resin, and permeability which is a property of the fibre bed. The starting point for modelling bulk flow is usually Darcy's Law, which is given here for flow in one direction [9]:

$$v = \frac{Q}{A} = \frac{K}{\mu}\frac{\Delta p}{L}$$

where v is the flow front velocity,
Q/A is the flow rate per unit area,
K is the permeability of the fibre bed,
μ is the resin viscosity (sometimes denoted as η),
and $\Delta p/L$ is the pressure gradient.

The permeability, K, is a measure of how easy it is for a fluid, in this case resin, to pass through a solid medium, in this case the fibre bed. It is affected by the amount of space between the fibres (porosity) as well as the geometry of this space. For anisotropic composites, permeability must be defined in each direction. The starting point for modelling permeability is usually the Kozeny-Carman equation:

$$K = \frac{R^2}{4k}\frac{\left(1-V_f\right)^3}{V_f^{\ 2}} \quad [9]$$

where R is the fibre radius,
V_f is the fibre volume fraction (porosity = $1 - V_f$),
and k is the Kozeny constant.

Successful application of this equation in practice has been limited [15]. Due to the complex nature of permeability, it must often be determined by experiment for the particular application being considered. There is still some debate over whether these measurements should be done with an advancing flow front or in an already saturated medium [9]. Some have also found differences in permeability with different fluids of similar viscosity [15], [9], a phenomena which is not accounted for in the Kozeny-Carman equation or Darcy's law.

Another term in Darcy's law is the resin viscosity. Reducing the viscosity increases the flow rate as well as leading to improved fibre wetout. As a result, the resin is sometimes heated during injection to reduce viscosity. It can be heated before the injection or as it comes into contact with the preheated mould. However, as described in the following section on cure, viscosity also increases as cure progresses and this process is accelerated with increasing temperature. Therefore, the injection temperature must be selected as a compromise between viscosity and cure rate.

The final term in Darcy's law is the pressure gradient caused by the difference in pressure between the inlet and the flow front. The progression of the flow front away from the inlet causes the injection length, L, to increase. For a constant pressure injection, the increasing injection length will result in a reduced pressure gradient and a decrease in the flow rate (Figure 2.1). If the mould length is too long, the flow rate may reduce essentially to zero. For a constant flow rate injection, the injection pressure must increase to maintain a constant pressure gradient across the increasing injection length (Figure 2.1). However, the equipment will require the injection pressure to be limited to some maximum value at which point the flow rate reduces as with a constant pressure injection.

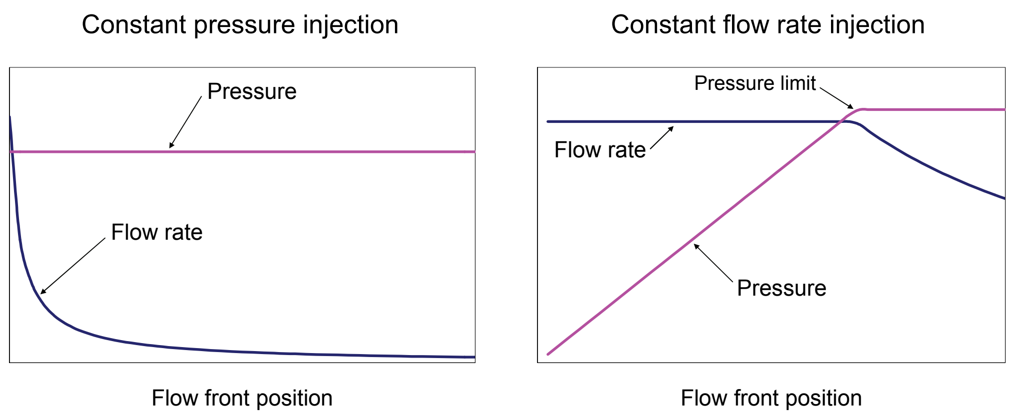

Figure 2.1: Progression of pressure and flow rate predicted by Darcy's law

2.5.2 Potential mould filling issues

One of the biggest issues with mould filling is racetracking, or edge effect, which occurs when variations in permeability allow the resin to flow faster in some areas than in others. If this is not accounted for in the injection strategy, air pockets can be formed where regions of faster flow meet ahead of slower regions. The difficulty is in predicting what variations in permeability might exist in the preform. For example, the deformation of fabrics during preforming alters the fibre architecture and resulting permeabilities [14]. Even with repeated parts made in the same mould, part to part variations can exist as a result of preform handling and shifting in the mould. Common locations for racetracking are along part edges and the outside of part radii (Figure 2.2) [9]. At part radii, the preform tends to compact more against the inside of a bend, while along part edges it is often difficult to ensure that the preform will fill the mould exactly to the edge.

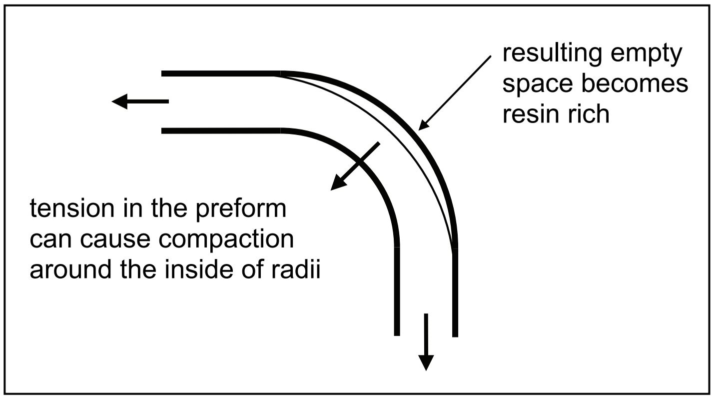

Figure 2.2: Potential site of racetracking along outside of part radii [9], [15]

Other potential problems with mould filling include fibre washout, flow on top of the reinforcement, shifting of a core, dry spots, and high void content at the outlet [9]. Fibre washout is the term used to describe the movement of fibres during injection. This can occur when the injection pressure is too high. For parts with very low volume fractions, it is also possible for the resin to push the preform to one side and simply flow by. Similarly a core can be moved or pushed to one side during injection. Dry spots and voids can result from either a poor injection strategy or volatile compounds escaping from the resin. Thick parts are particularly susceptible to many of these mould filling problems [9].

A number of best practices have been suggested over the years to avoid problems with mould filling. These include gating at the lowest point and venting and highest point, allowing pressure to build up in the mould after filling to decrease void content, and changing from a point to a line source to reduce injection pressure and the likelihood of fibre washout [14]. Some practical suggestions have also been proposed to minimize void content [9]:

- use vacuum assistance
- de-gas the resin before injection
- ensure the vacuum level is not so low that volatile compounds in the resin escape
- ensure the entire injection cavity, including gates and vents, is vacuum-tight

- ensure the injection pressure is not so high as to break the mould seal
- allow resin to flow out of the mould until it contains no more bubbles (bleeding or "burping" the mould)
- after closing the outlet, build up a high cure pressure inside the mould
- do not cure at too high a temperature
- increase bleeding time if voids persist (if this works the gate is badly placed)

2.6 Curing

Thermoset resins for RTM begin in a liquid form. Curing is the process in which the polymer chains of the resin are cross-linked by chemical reaction to form a three dimensional, solid network [14]. The reaction accelerates with increasing temperature. Ideally for RTM, the reaction should proceed as slowly as possible during injection to maintain a low viscosity and then as quickly as possible upon mould filling to reduce cycle time (Figure 2.3). The injection temperature must be selected carefully as a trade-off between increasing temperature to reduce viscosity and reducing temperature to slow down curing. The rest of the cure cycle should be optimized to minimize the cycle time, residual stresses, warping, void formation, and surface quality [9].

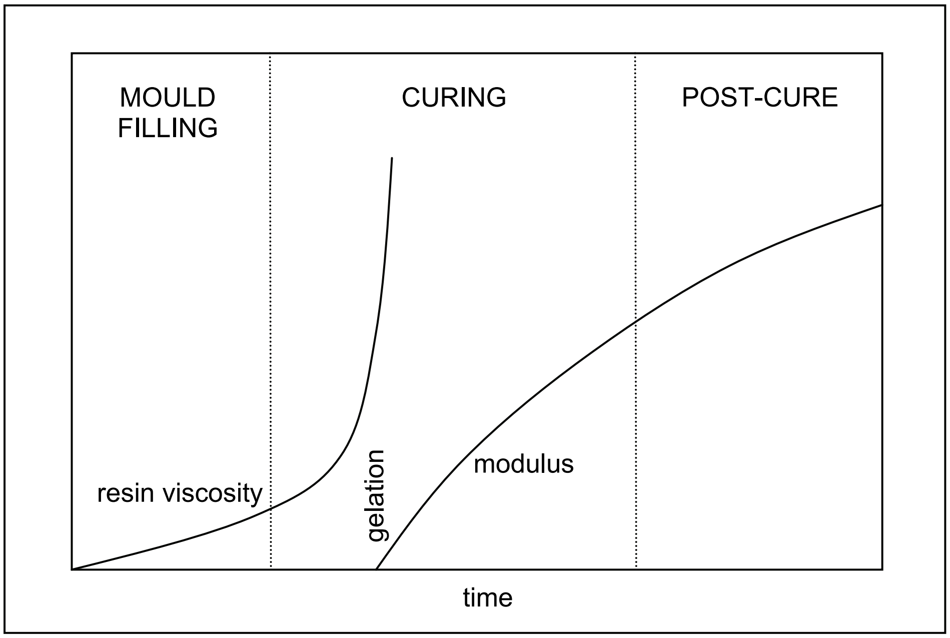

Figure 2.3: Viscosity and modulus changes during cure [14]

Instead of waiting for the part to cure completely in the mould, it can be demoulded early and post-cured in an oven. This can improve throughput by freeing up the mould for the next part and this post-cure is also no longer limited by the service temperature of the mould [14]. If the part is to be post-cured, its "green" strength, or strength after gelation but before complete cure, must be sufficient for handling [14].

An important aspect of the curing process is the exothermic heat given off by the reaction. This can cause the system to be self accelerating. Careful design of the cure cycle makes use of the exotherm to help bring the resin up to the desired curing temperature. However, improper consideration of the exotherm can lead to excessive temperatures that char or otherwise damage the material.

Other issues with cure include porosity due to the evaporation of gases in the resin, incomplete cure, and poor surface finish as a result of resin shrinkage [9]. Chemical shrinkage of the resin during cure, as well as thermal expansion and contraction, can also lead to residual stresses in the part. These stresses can cause dimensional changes in the part called "springback" in certain shapes such as open section brackets. Residual stresses can also lead to delamination and other premature failures in the part. As with mould filling, thick parts are again particularly susceptible to many of these curing problems.

2.7 Process modelling

In the past, trial and error methods were often used to design the preform, mould, and process [17]. Process modelling attempts to model the various phenomena that occur during RTM in order to design and tailor the process for optimum results. These phenomena include resin flow, heat transfer, and cure kinetics. The information obtained from process modelling can be used to avoid dry spots, minimize mould filling time, ensure the mould can withstand injection pressures, obtain the required degree of cure throughout the part, minimize residual stresses in the part, and anticipate "springback" effects. The processing parameters that are affected include resin selection, injection pressure or flow rate, injection temperature, cure temperature, cure time, as well as mould design features such as gate and vent locations.

Accurately modelling the entire RTM process is complex and this is an area of considerable ongoing research [17]. However, simple models and approximations are often sufficient to produce parts of acceptable quality. The level of detail required in each aspect of process modelling greatly depends on the application. For high-volume production, mould filling time might be an important parameter to minimize. However, for high-end aerospace components produced in smaller quantities, part quality might be of greatest concern with mould filling time essentially irrelevant.

The preforming stage can be modelled to predict deformation of the fibre architecture [19]. Particularly with cut and paste of fabric, the final fibre architecture in a part can be quite different from that of the undeformed fabric [19]. This can have a significant impact on mould filling patterns as well as the structural integrity of the part [14].

Modelling the flow of resin during mould filling is the most common area of process modelling carried out for RTM. The bulk flow of resin through the preform can be modelled using numerical methods with the most general case involving three-dimensional flow in an anisotropic medium. Darcy's law and mass conservation are commonly solved together using a control volume finite element method [14]. With this flow model, potential dry spot locations, filling time, and pressure distribution can be determined. Virtual trial and error injections can be carried out to select ideal vent and gate locations.

These flow models tend to consider only bulk flow since modelling the flow between and within fibre bundles simultaneously is very difficult [20]. Flow within the bundles can be considered by adding a sink factor to the bulk flow model that accounts for a "loss" of resin into the fibre bundles. It is important to note, however, that voids can occur if the macro (bulk) and micro (fibre wetting) flow fronts progress at different speeds and modelling this behaviour would be an important addition to flow simulations [12].

Finally, the curing process can be modelled with a cure kinetics equation that sets the degree of cure (α) as a function of time and temperature [12]. The degree of cure varies from zero for completely uncured to one for completely cured. Other properties such as viscosity, chemical shrinkage, heat transfer coefficient, and coefficient of thermal expansion can then be predicted as functions of the degree of cure. Cure modelling can help design the cure cycle to obtain optimal mechanical properties for the part as well as to predict residual stresses and "springback" in the part. However, cure modelling is still not common in industry due to the effort, particularly experimental, required to obtain a valid model [9].

Both the flow and cure models generally require heat transfer modelling since many properties such as viscosity and degree of cure are strongly influenced by temperature. Such an analysis would consider the heat applied to the mould as well as the heat generated during the exothermic curing reaction. In addition, a complete process model should consider flow and cure simultaneously. In practice, however, the RTM process is usually designed to delay significant curing until after the mould has been filled. In these cases, the analysis can be greatly simplified by considering the two stages separately.

2.8 Mould design

Mould design and construction is considered the most critical factor in successful RTM [14]. In RTM, it is the mould which dictates the geometry and tolerances of the part, how the resin will flow into the part, and how the part will be heated. The mould must react all loads applied during closure and injection, maintain an airtight seal when vacuum is employed, and withstand repeated handling in a production environment over the course of its lifetime [15]. The ideal mould should "provide dimensional stability during use, be easy to fabricate, maintain, and repair, and be convenient to handle and store" [18].

Due to the critical nature of the mould in RTM, it is essential that the mould be designed concurrently with the part, rather than sequentially [15]. In fact, all aspects of part manufacture should be considered during the part design. Even seemingly minor changes such as part thickness or fibre volume fraction are very difficult to change once the mould has been machined. This problem is much more acute in RTM than in, for example, autoclave processing where there is only a one-sided rigid tool. In the study conducted by NASA about lessons learned in the composites industry, perhaps the most repeated theme is the need for a concurrent or "integrated engineering team" approach to design [6]. There is specific mention of the need to integrate the tool design and material selection with the part design; producibility is essential to the design of a composite structure.

A number of pertinent mould design "truths" are proposed by [18]:

- There is no such thing as low-cost tooling – unless it produces a quality part at low cost.
- The materials used in the moulds and tools account for the smallest part of the cost.
- It costs less to correct a tool or mould than to correct the moulded part or bonded assembly.
- Good moulds and tooling encourage good workmanship. Poor tools encourage inferior workmanship.
- The damaging effects of a poor quality mould will linger long after the benefits of its initial low cost are gone.
- Quality cannot be inspected into a part. It can only be built into the mould or tool.
- The quality of a part is only as good as the quality of the mould that produced it.

2.8.1 Mould material

No single mould material is suitable for all applications [18]. A great variety of mould materials exist each with strengths and weaknesses appropriate to different applications. These materials can be classified based on the three main methods of mould construction: the direct method, indirect method, and hybrid method [15], [9]. The direct method involves machining the mould cavity directly out of a block of material. Materials in this case include polymers, tooling foams, metals, and machinable ceramics. The indirect methods involve laminating or casting the tool faces onto a master model. Materials in this case include castable polymers, glass or carbon fibre reinforced plastics, castable ceramics and concrete, nickel electroforms, or sprayed metal. Finally, hybrid methods involve machining the tool face from a near-net casting. Materials in this case include cast iron or aluminum. This category can also include lightweight tool faces that are supported by framing materials.

A number of properties must be considered for the mould material selection. Stiffness of the mould is considered to be the main contributor to achieving desired part tolerances [9]. The mould must resist both the injection pressure of the resin as well as the compaction pressure of the dry fibres, which can in some cases be as high or higher than the injection pressure. The stiffness of the mould must be such that dimensions remain within their acceptable tolerances and that the mould seal is maintained.

Another important material property to consider is the service temperature. High temperature cures may necessitate a metal mould [14]. Other important properties include density, heat capacity, thermal conductivity, coefficient of thermal expansion, durability, ease of machining, price, acquisition time, ability to repair or modify, release properties , and chemical compatibility with resins and release agents [9], [15].

Aluminum, steel, and invar are the most common metals used for moulds made by the direct method. Aluminum is easy to machine but has the highest coefficient of thermal expansion of the three and is susceptible to surface damage during handling. Invar is expensive, heavy, and difficult to machine, but is a candidate for moulds because it has a very low coefficient of thermal expansion comparable to that of carbon [21]. Steel falls between aluminum and invar in its properties.

Finally, it should be noted that flexible mould materials can also be useful [14]. This is particularly true for hollow parts where an inflatable bladder can be used to fill a cavity with a complex shape. The geometry of a hollow part is much more limited for a solid mandrel or insert that must be removed after cure. The drawback of using flexible mould components is that the injection pressure cannot be as high.

2.8.2 Heating and cooling

The most basic method for heating an RTM mould is with a hot air oven [11]. Another simple and low-cost option is to place the mould in a hydraulic press with heated platens, though this requires a mould with high thermal conductivity. The preferred but more expensive approach is integral heating of the mould which provides faster heat up times and better temperature control. The most common integral method is to circulate water or oil through the mould, which has the added benefit of also allowing mould cooling [14], [9]. Another method of integral heating is with electrical cartridge or resistance heaters [11].

An important parameter to consider in the mould design is the thermal expansion of the part and mould material upon heating. For exact duplication of a complex geometry, an ideal mould would be made of the same material as the part [18]. However, this is not possible in many situations, particularly for resins that cure at high temperature. Differences in thermal expansion between the part and mould can be accounted for using finite element analysis. A less accurate but simpler method is to apply a shrink factor to all the mould dimensions based on the difference in thermal expansion between the part and mould [18].

2.8.3 Clamping

The mould must be clamped shut such that the mould seal and part tolerances within the cavity are maintained throughout the injection and cure. The simplest choice for mould clamping is to use threaded bolts. However, a hydraulic press may be more appropriate for high volume production or where additional support of the mould faces is desired. It is important to note that clamping forces can be high, particularly for large parts [9]. The mould closure force required can be due as much to preform compaction as to the resin injection pressure.

2.8.4 Sealing

Mould sealing is important in RTM to avoid wasting resin and is essential when using vacuum assistance. It is generally considered best practice to seal on a flat surface [9]. O-rings or other flexible seals are the most common method of sealing as they do not require high-precision machining of the mating surfaces. A variety of gaskets and seals are possible, including hollow o-rings or rubber tubes that can be pressurized to improve performance [9]. Though some argue that o-rings are the only practical way to seal a mould [14], others argue that due to the frequent cleaning required of cured resin in o-ring grooves, a metal-to-metal seal is preferred for high-volume production [11].

2.8.5 Modular moulds

The concept of a modular mould has been borrowed from the injection moulding industry and used successfully to create cost-effective moulds for RTM [22], [23]. The idea is to create a heated, sealed mould cavity with built-in gates and vents that can be re-used for a variety of different parts. Moulding a new part geometry simply requires machining a new set of inserts to fit within the cavity. This greatly reduces the design and machining requirements for a new part since most of the mould complexities such as heating, sealing, clamping, and interfacing with the injector are already taken care of with the re-usable cavity. In addition, preforming of parts can be carried out with just the inserts, leaving the mould cavity free for other injections thereby improving throughput. Since production of the mould constitutes perhaps the most significant up-front cost for RTM, the modular mould concept is a crucial step toward the goal of making RTM a cost-effective composite manufacturing method.

2.9 Future directions

The RTM process shows considerable promise as a composites manufacturing method for a variety of industries. Though it has been around for some time, its adoption has been slow due largely to perceptions of high up-front costs for tooling and high process variability. With advances in tooling and process design, these concerns are gradually being alleviated.

Process modelling has advanced considerably to eliminate the need for costly trial and error methods to determine process parameters. Optimization techniques such as neural networks and genetic algorithms are now being applied to these models to, for example, find the optimum location for gates and vents [24]. In fact, optimization techniques are being applied to all facets of the RTM process including manufacturing cost [25].

Despite the ability to now accurately model important aspects of the RTM process such as mould filling, sensitivity to input parameters remains a problem. Effects such as racetracking often vary from part to part due to slight inconsistencies in preform fabrication. In order to make the process more robust, there is a current research effort into the active control of RTM injections. By placing sensors strategically in the mould, gates and vents can be controlled to reduce the maximum injection pressure, reduce fill time, and avoid dry spots [14]. Some studies approach the problem by defining a number of mould filling scenarios, using a variety of optimization techniques to determine the best injection parameters for each scenario as well as determining the minimum number of sensor locations needed to distinguish between the scenarios, and finally incorporating these results into a computer control system that implements the appropriate injection parameters based on real-time sensor data [26], [27].

Finally, careful implementation of the RTM process into a production environment is key to its success. One of the promising characteristics of RTM is its potential for automation in preforming, part loading, injecting, and demoulding. In conjunction with a lean manufacturing approach, RTM offers the possibility for cost effective production of composite parts [28]. The lean manufacturing approach for RTM involves encouraging a continuous flow of material through the plant, minimizing scrap material and wasted time, and using flexible and adaptable equipment such as modular moulds.

2.10 Summary

RTM is a cost-effective method for producing composite parts with a good surface finish and complex geometry. These and other advantages of RTM are being brought to bear in CRIAQ Project 1.15 for the production of an aeronautical component. Although RTM has been used for some years now, there remain many areas for potential improvement, including in mould design and the design of parts for manufacturability. These aspects of the project are discussed in the following chapter.

Chapter 3 Design

3.1 Introduction

One of the goals of CRIAQ project 1.15 was to demonstrate resin transfer moulding (RTM) technology being developed by producing an actual part. The part selected was the leading edge slat of the Bell 407 helicopter. The part currently in service is an assembly of metallic components and fasteners. The goal of this project is to consolidate this assembly into a single composite part.

Before producing a full-size slat, a prototype was produced consisting of a representative section of the slat. This was a cost effective means to verify the proof-of-concept of the design, try out different bracket options, and provide samples for mechanical testing. Lessons learned from the prototype will be applied to the design and production of the full-size slat.

The design of a composite structure is a complex task that requires a concurrent approach. Not only must the design satisfy operational requirements such as strength and durability, it should also be a design that can be manufactured reliably and at low cost. Therefore, tasks for this project such as stress analysis, preform design, mould design, and process modelling were all carried out in parallel rather than sequentially.

This chapter deals with the design of the prototype slat and process from a manufacturability perspective as well as the design of the mould used to produce the prototype. These design tasks were closely related and included issues such as preforming, mould machining, demoulding, and post-machining. Stress analysis and process modelling, including flow modelling, were conducted as separate tasks but always in close coordination with the work presented here. This design process was iterative with changes as a result of one perspective requiring the design to be re-evaluated from the other perspectives.

Solid modeling with PTC Pro/ENGINEER Wildfire 2.0 was used extensively in the design of the part and mould. The same solid models were used by the various members of this collaborative project to define the geometry for such tasks as flow modelling, stress analysis, mould design, and mould machining.

3.2 Design problem and constraints

The Bell 407 helicopter has a one-piece aluminum honeycomb horizontal stabilizer with an auxiliary fin at each end [1]. Because this is a lightweight helicopter, the stabilizer is fixed at a single incidence angle and contains no movable control surfaces. Slats are therefore installed on the leading edge of the stabilizer (one on each side of the tailboom) to improve airflow conditions at high angles of attack and slow speed.

The metallic slat design consists of a hollow airfoil fastened to four attachment brackets which are in turn fastened to the stabilizer with two fasteners each (Figure 3.1). A variety of bracket designs have been used and in some cases the airfoil has been divided into three segments to improve compliance in bending.

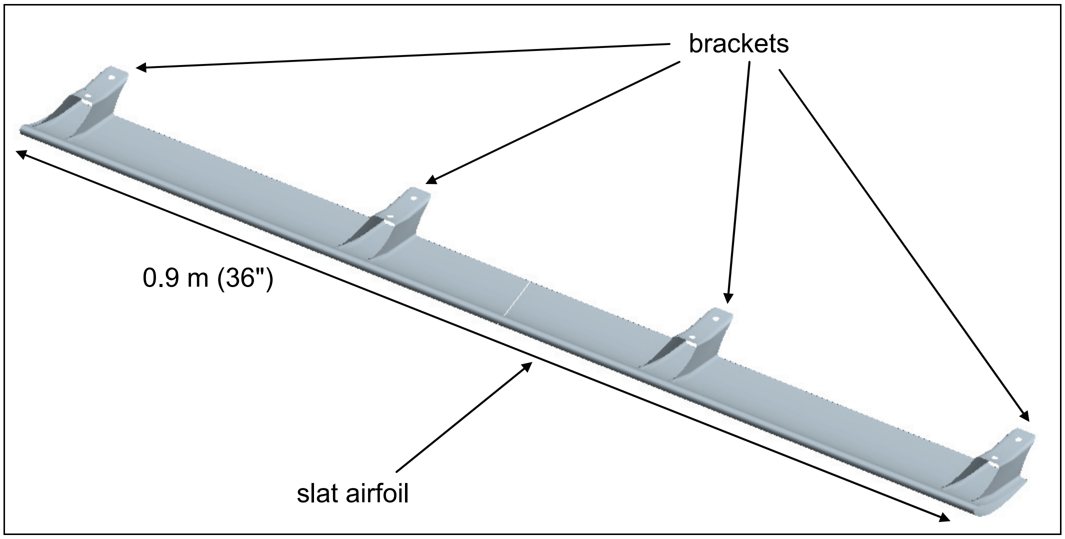

Figure 3.1: Example of slat with full brackets

The design problem for this project was to produce a slat airfoil with four attachment brackets as a single part. The eight fasteners attaching the brackets to the horizontal stabilizer were to remain for interchangeability of the composite slat with existing metallic slat assemblies.

The integrated brackets provided the main challenge for this design. Their complex geometry could lead to stress concentrations, dry spots during mould filling, and springback after cure. From a mould design perspective, the brackets created "trapped" regions regardless of mould opening direction. A simple two-piece mould with a single parting plane was therefore not possible; removable inserts or bladders would be required in the trapped regions, including in the hollow airfoil.

The problem was further complicated by constraints on the part geometry. The airfoil cross-section and position had to be the same as with the existing metal slat and the brackets had to follow the stabilizer profile at the mating surface. These curved shapes lead to challenges in preforming and mould machining. In addition, the cross-sectional dimensions of the part are small: the slat chord length is approximately 80 mm (3"), the slat thickness is less than 10 mm (0.4"), and the bracket span between the slat and horizontal stabilizer is less that 20 mm (0.75") (Figure 3.2). These small dimensions made it difficult even to simply fit the desired number of plies within the required design envelope. For example, the trailing edge of the slat airfoil has a thickness of only four plies of the carbon fabric that was selected to make the part.

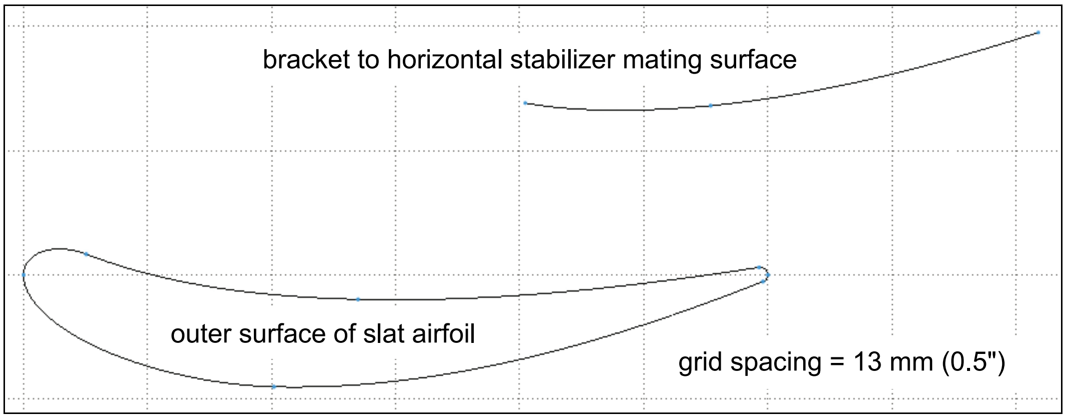

Figure 3.2: Required cross-section of slat airfoil and bracket

3.3 RTM equipment and facilities

RTM injections of the part and prototype were to be carried out using the equipment and facilities at AMTC. The equipment available included two custom made modular mould cavities. The cavities were roughly 100 mm (4") thick and 300 mm (12") wide with one being 1.2 m (48") long and the other 0.5 m (18") long. Re-using these cavities was a considerable advantage because all that had to be designed and produced for a new part was a set of inserts to fit within the cavity. The dimensions of the full-size slat require the use of the larger mould cavity. In order for the prototype to be cost-effective, it was made to fit within the smaller mould cavity (Figure 3.3). Though it was possible to add resin ports to the mould cavity, it was preferable for the inserts to be designed such that resin channels met with the three existing ports. Finally, P20 tool steel was the suggested material for the mould inserts because it was the material used to make the mould cavities, it is durable and has a relatively low coefficient of thermal expansions, and it was used successfully to make inserts for the same mould cavities on previous RTM projects.

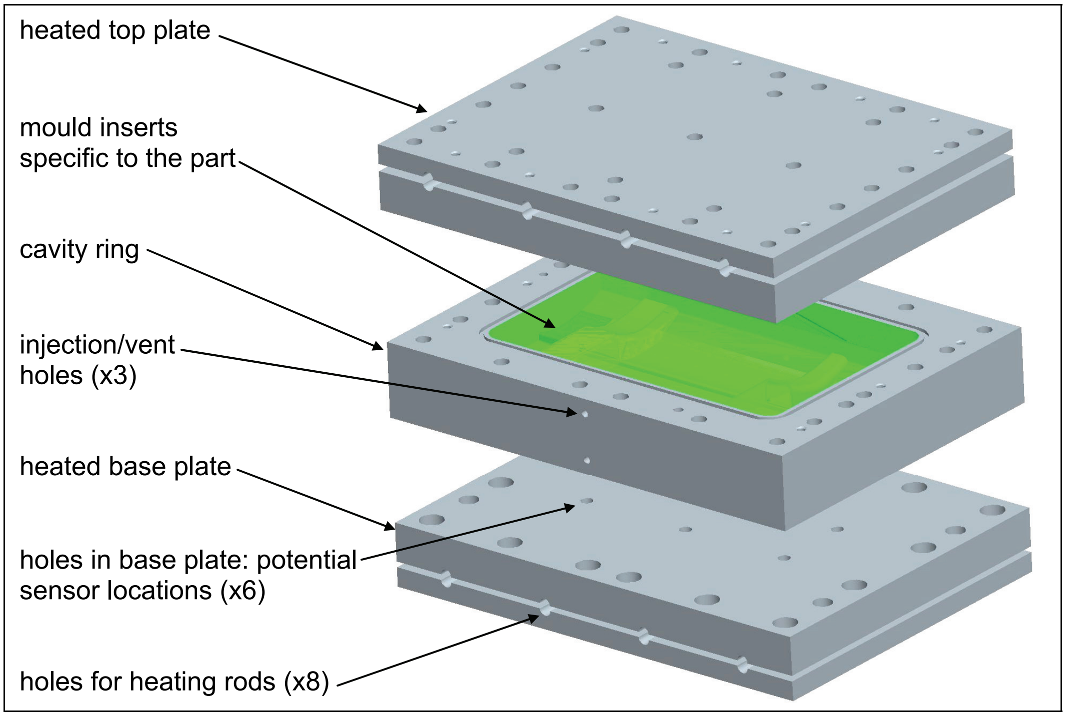

Figure 3.3: Existing prototype modular mould cavity

3.4 Pertinent results from external analyses

As mentioned above, this was a collaborative project and a number of analysis tasks were conducted in parallel to the part and mould design. Pertinent results from these analyses are presented in this section. Though some results were obtained before the part and mould design began, most were obtained as the design progressed. They are presented all together in this section for clarity and not to indicate chronology.

3.4.1 Part material selection

A material selection was carried out for the composite slat taking into consideration mechanical property requirements, service temperature, suitability for RTM, and availability [29],[30]. The resin selected was CYCOM 890 RTM made by Cytec Industries Inc. This is a one-part epoxy resin system with properties well suited to RTM [31]:

- 30 day pot life at room temperature
- 12 month shelf life at -18ºC
- Injectable at 80ºC with 24h pot life
- 0.25 Pa·s (250 cps) initial injection viscosity
- Cures in 2 hours at 180ºC
- 160ºC continuous hot/wet service performance
- Glass transition temperature ~200ºC

A number of fibre options were proposed but a 5-harness satin woven carbon fabric also made by Cytec Industries Inc. was selected for the prototype slat (CYCOM 890-1 Prepreg/RIGIDITE 890-1 WG30-500 6K 5HS). This fabric is pre-impregnated with a small amount of resin which makes it tacky on one side to aid in preforming.

3.4.2 Part stress analysis

A preliminary stress analysis was carried out on the full-size slat [32]. Based on this analysis, the proposed lay-up was $[\pm 45]_4$ for the slat airfoil and $[(0/90) / (\pm 45)_2]_s$ for the brackets. Note that each ply of fabric contains fibres at 90º to each other and is therefore (0/90) or (±45) by nature. It was also determined that three bracket configurations were possible: full brackets, inward facing half brackets, and outward facing half brackets (Figure 3.4). These could also be combined in a variety of ways. Also, the angle of the bracket sidewalls could be varied. The preliminary stress analysis results indicated no significant preference for any of these bracket designs. Recommendations from the prototype manufacturing trials as well as further stress analyses would therefore be needed to select a final bracket design for the full-size slat.

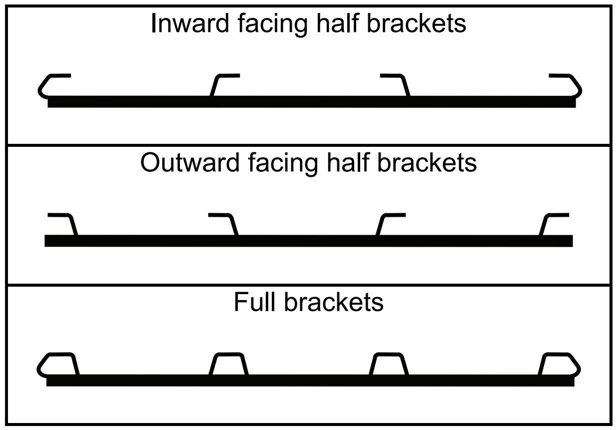

Figure 3.4: Three possible bracket configurations

3.4.3 Mould filling analysis

A number of flow modelling simulations were carried out by researchers at École Polytechnique de Montréal [33]. Although these simulations were carried out for the full-size part, the same injection strategy would be used on the prototype for validation. These simulations demonstrated that the best way to inject the part would be in the chord-wise direction from the trailing edge with a vent along the leading edge. Edge effects would play an important role, particularly along the edge of any half brackets.

3.5 Conceptual design of the mould

Beginning with approximate dimensions and a simplified geometry of the full-size slat with outward-facing half brackets, a conceptual design of the modular mould inserts was created (Figure 3.5). This design consisted of upper and lower halves, small inserts under each bracket, and a mandrel or bladder inside the airfoil (not shown in the figure). It was evident at this stage that bracket inserts would be required regardless of mould opening direction or whether the brackets were full or half.

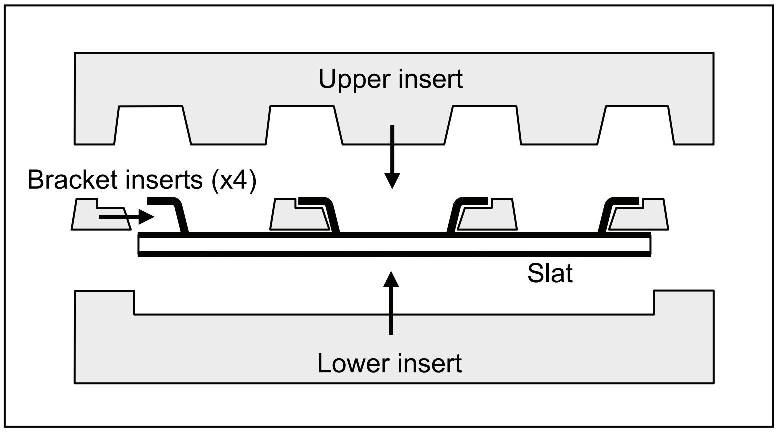

Figure 3.5: Preliminary mould concept

Some important guidelines for the mould design were established at this point. The design should have as few inserts as possible. Internal edges (two surfaces meeting) are acceptable and can be easier to clean than rounded edges though they may not be convenient to machine. Internal corners (three edges meeting) are not acceptable because they are difficult to clean and essentially impossible to machine. Though seemingly obvious, consideration must also be given to how the preform and mould inserts will be assembled into the mould and how, after curing, the inserts and now solid part will be removed (demoulding).

3.6 Prototype configuration

The dimensions of the prototype mould cavity were such that the prototype part could have full-size brackets and a full-size airfoil cross-section. However, the length would have to be slightly less than half that of the full-size slat. By including a number of brackets and a portion of the airfoil, all the features of the full-size slat could be verified for manufacturability. It was also desirable to try out some of the different bracket options suggested from the stress analysis to evaluate their manufacturability. Although more brackets could have fit on the prototype, two were selected to avoid an overly complex mould and so that the bracket spacing would be the same as on the full-size slat. The final configuration of the prototype slat is shown in Figure 3.6.

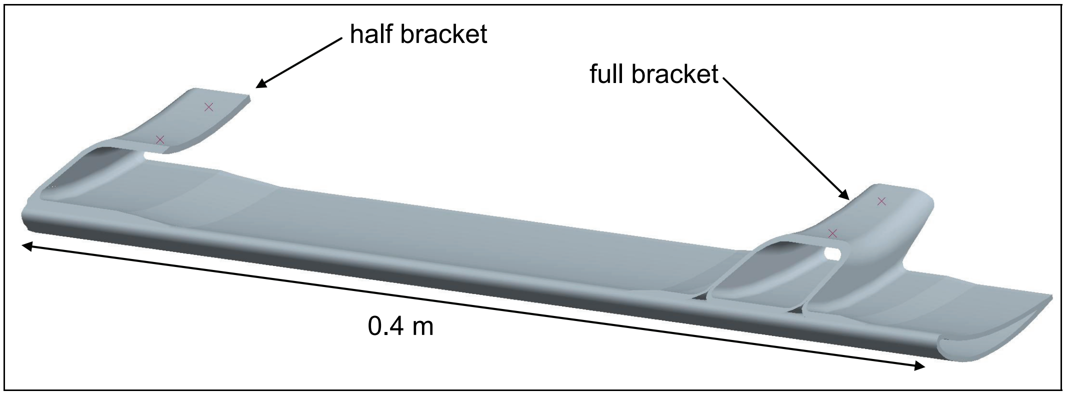

Figure 3.6: Solid model of prototype slat

The cross-sectional side profile of the airfoil and brackets was constrained by the design requirements as shown in Figure 3.2. The bracket spacing was, as with the full size slat, determined by the spacing of the fasteners used to attach the slat to the stabilizer. The selection of bracket types and details of their design and dimensions are presented in the following sections.

3.7 Bracket design

An important issue in the slat design was the bracket to airfoil connection. The metal design used "C", "S", or hat shaped brackets attached to the airfoil with fasteners. As with most composite designs intended to replace metallic parts, a direct copy of the metal design was not appropriate. For example, the metal half brackets were attached to the airfoil with a single flange and fasteners (Figure 3.7). The composite design eliminated the fasteners by moulding the brackets and airfoil as a single part. However, the composite design required a second flange to stabilize the bracket to airfoil connection and prevent delamination. In addition, the ends of the bracket flanges were tapered with ply dropoffs to minimize stress concentrations at these thickness changes. Also, from a mould design perspective, the sidewalls of the brackets included appropriate draft angles to facilitate mould opening. Finally, the bracket corners required generous radii both to facilitate manufacturing and to avoid high stresses at these locations.

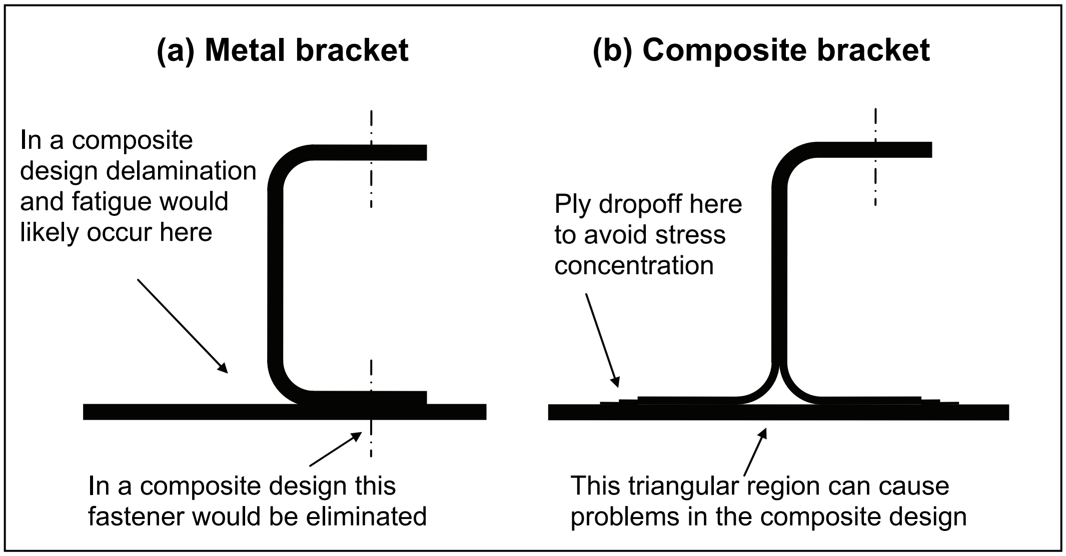

Figure 3.7: Metal and composite half brackets

From a manufacturing perspective, the triangular region at the bracket to airfoil intersection created by the composite redesign was not ideal (Figure 3.7b). If left as is, this region would fill with resin and cause racetracking during mould filling. This resin rich region might also be a site for micro-crack formation as the resin shrinks upon curing but the surrounding material is constrained by the fibres [15]. These problems can be minimized by filling the space with tows of unidirectional fibre (sometimes called a "noodle").

An alternate bracket design was proposed that eliminated the triangular junction. The brackets at the ends of the airfoil could simply extend continuously from the airfoil material (Figure 3.8). Although this was a potentially improved design, it also presented a number of drawbacks. It could only be applied to the end brackets which meant that the slat would have two different bracket types and the triangular junction would still be present on the internal brackets. It also resulted in a complex geometry that might be difficult to preform and, as discussed below, might be difficult to post-machine.

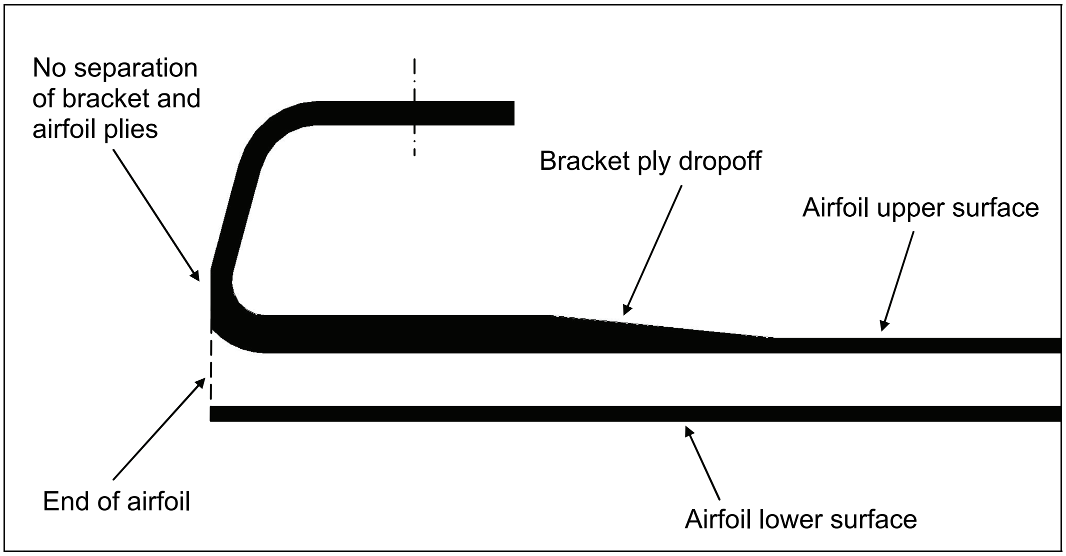

Figure 3.8: Blended half bracket

With the addition of this blended option, four bracket types were available as design options (Figure 3.9). These could be categorized as full or half, and blended or non-blended. Full brackets offered improved structural integrity but with increased manufacturing complexity over the half brackets. Likewise, blended brackets over non-blended brackets. Note that the blended designs are only possible for the brackets at the ends of the slat. Also note that the only non-blended design possible at the end of the slat is an outward facing half bracket. This is due to space constraints on the flanges attaching the bracket to the airfoil.

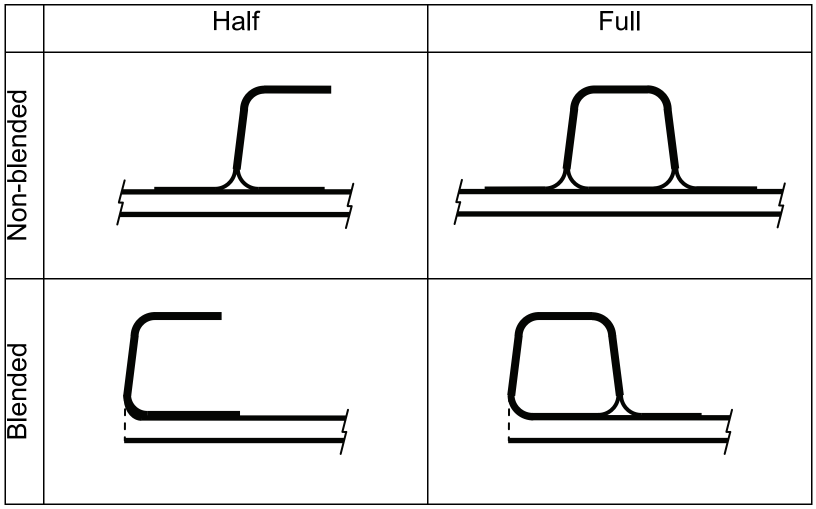

Figure 3.9: Four bracket types

The two brackets for the prototype were selected to have the more complex option from one category paired with the simpler option from the other category: one blended half bracket and one non-blended full bracket. This allowed each category to be present without having any overly complex brackets. The non-blended full bracket was representative of an internal bracket and the blended half bracket representative of an end bracket.

3.7.1 Non-blended full bracket

For the full bracket on the prototype slat, the final configuration and dimensions are shown in Figure 3.10. The design included two triangular junctions which were unavoidable. On either side of the bracket, the plies were stepped down gradually in ply dropoffs to avoid stress concentrations. A small draft angle was required on the vertical sidewalls to facilitate mould opening. In addition, a small horizontal draft angle was included on the sidewalls to facilitate removal of the bracket insert that would be required to mould the full bracket. An analysis was carried out in Pro/ENGINEER to confirm that the full bracket insert could theoretically be removed without interference with the part.

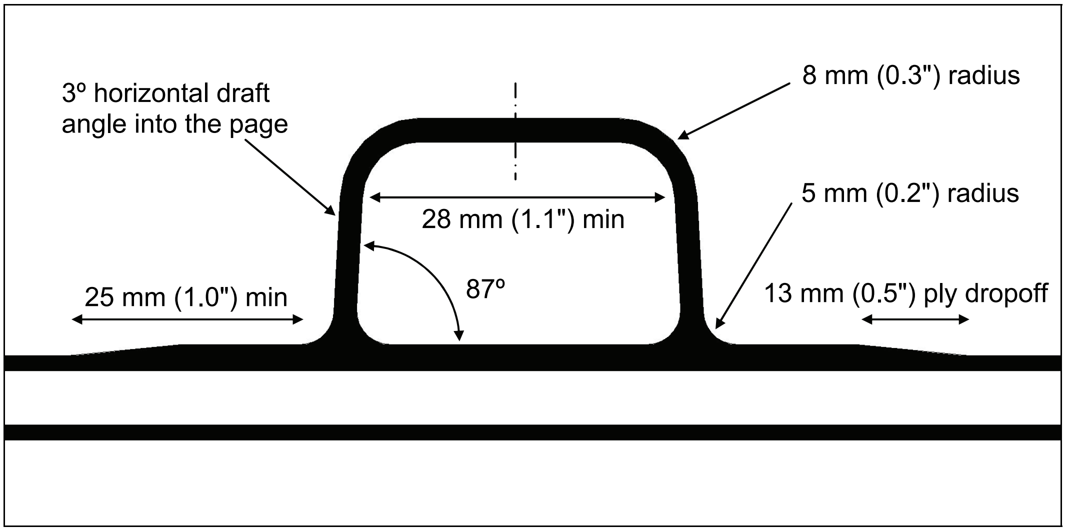

Figure 3.10: Full bracket dimensions

Bracket radii, lower flange widths, and ply dropoff lengths were selected based on stress analysis results and manufacturing experience. For example, a general rule of thumb states that radii should be no less than three times the laminate thickness [9]. The two upper bracket radii were set to 8 mm (0.3") where the laminate thickness is 2.5 mm (x 3 = 7.5 mm), while the four lower radii at the bracket junctions were set to 5 mm (0.2") where the laminate thickness is 1.1 mm (x 3 = 3.3 mm). In addition, the upper flange width was selected to be at least as large as on the existing metallic design. Note that the sidewalls were defined by a flat plane angled relative to a horizontal plane passing through the airfoil chord. As this sidewall plane intersects the curved surfaces of the airfoil and bracket upper flange, it forms intersection lines that are also curved. Therefore, only the minimum values of certain dimensions in the figure are provided since these will vary depending on where the cross-section is taken.

3.7.2 Blended half bracket (end bracket)

To achieve the blended half bracket design, two options were possible. The actual airfoil plies could be extended and wrapped around to form the bracket, or new plies for the bracket could be placed onto the airfoil as with the non-blended brackets. The preforming and post-machining appeared more complicated with the extended airfoil material option, so the bracket was made with six new plies placed on top of the airfoil as with other brackets (Figure 3.11). To avoid a sharp separation point between the airfoil and bracket plies, the end of the airfoil was expanded so the upper surface would follow the beginning of the bracket contour (Figure 3.11). The design of this expanded airfoil is revisited in the section below on excess material and post-machining.

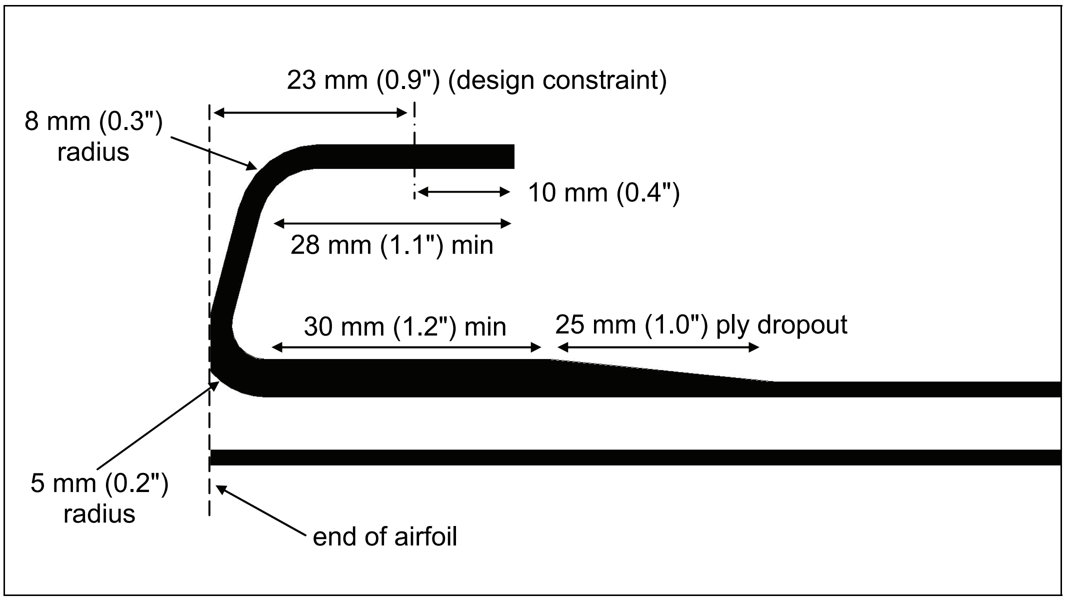

Figure 3.11: Blended half bracket dimensions

Bracket radii, flange widths, and ply dropoff lengths were made consistent with the full bracket. In this case, the fastener holes were next to a free edge. The edge distance was made the same as on the existing metallic designs (10 mm). The distance between the end of the airfoil and the last set of fasteners (23 mm) is constrained by the design requirements. Therefore, for a given upper flange width, the bracket sidewall must assume a particular draft angle, in this case 15º.

3.8 Excess material and post-machining

Consideration of part edges was one of the most difficult steps in designing the part for manufacturability. Although it is in theory possible to mould a net-shape part, in practice it is not always worth the added effort to do so [9]. In particular, it is difficult to preform a part with a clean edge that exactly fills the mould. If the fibres extend too far they may get pinched when the mould is closed which can damage the mould. If the fibres do not extend far enough, a resin rich region is created along the edge which can lead to racetracking and microcracking. It is often easiest to simply add excess material along all part edges. This excess material can be trimmed off in a post-machining stage to leave the final part with clean edges free of any defects. From this standpoint, the ideal prototype slat would have excess material along all free edges (Figure 3.12).

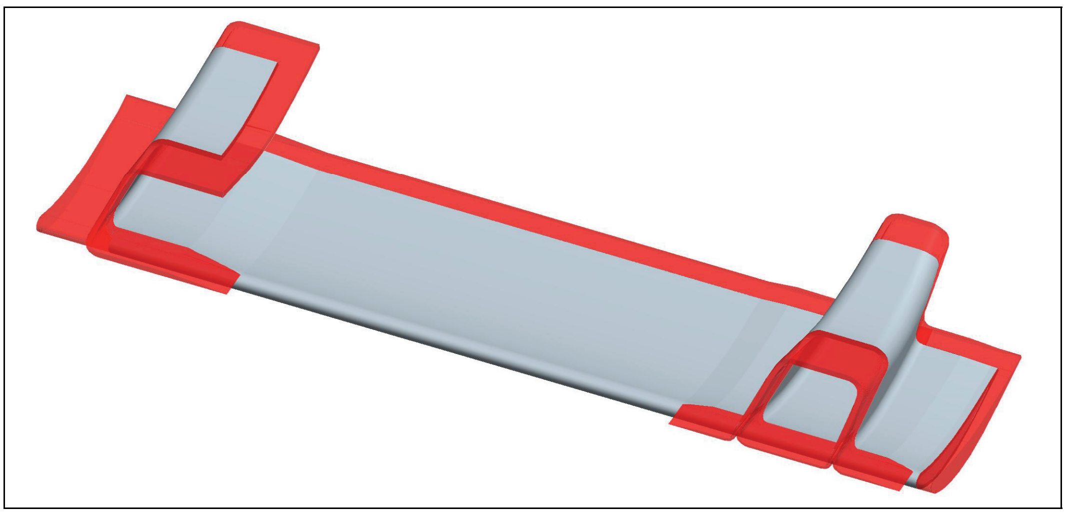

Figure 3.12: Excess material ideally added to all free edges of the part

3.8.1 Airfoil trailing edge trimming

The trailing edge of the slat airfoil has a thickness of four plies and a radius of two. Since the design specifies a slat thickness of four plies, wrapping all the plies around the trailing edge was not an option. Therefore, the trailing edge was also considered a free edge where excess material should be added to be later trimmed in post machining. Two plies from the top and two from the bottom had to drop off so the two surfaces would meet with a final thickness of four plies (Figure 3.13).

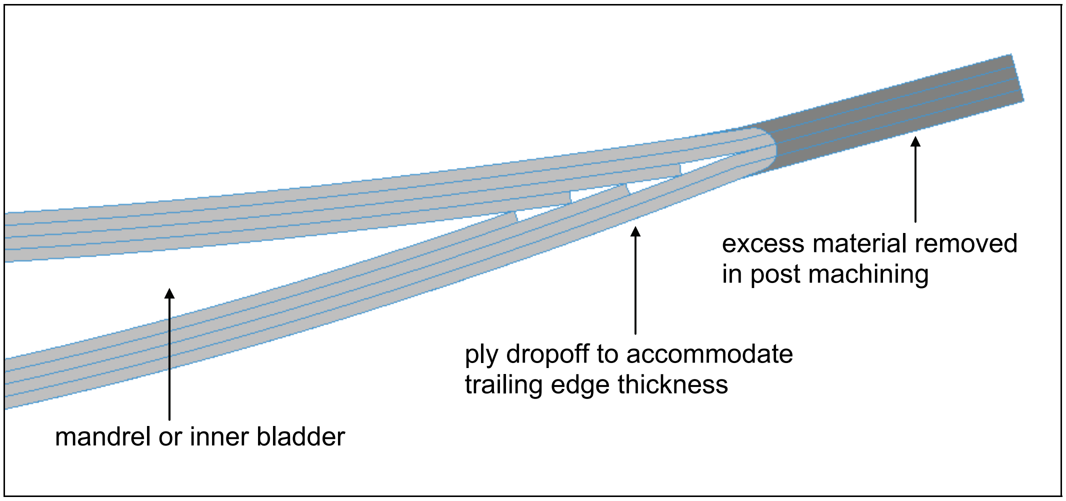

Figure 3.13: Ply dropoff and excess material at airfoil trailing edge

3.8.2 Bracket trimming

Trimming the excess material along the airfoil and bracket trailing edges appeared straightforward. The greater challenge was at the leading edge where the extra bracket material had to somehow separate from the airfoil surface (Figure 3.14). As mentioned in the bracket design section above, such a separation is very dangerous as it presents an ideal crack initiation site. Removing all traces of the excess material would therefore be critical but very difficult to do without damaging the airfoil surface. In addition, the mould insert required to fill this sharp separation point would be fragile, making it difficult to machine, handle, and demould.

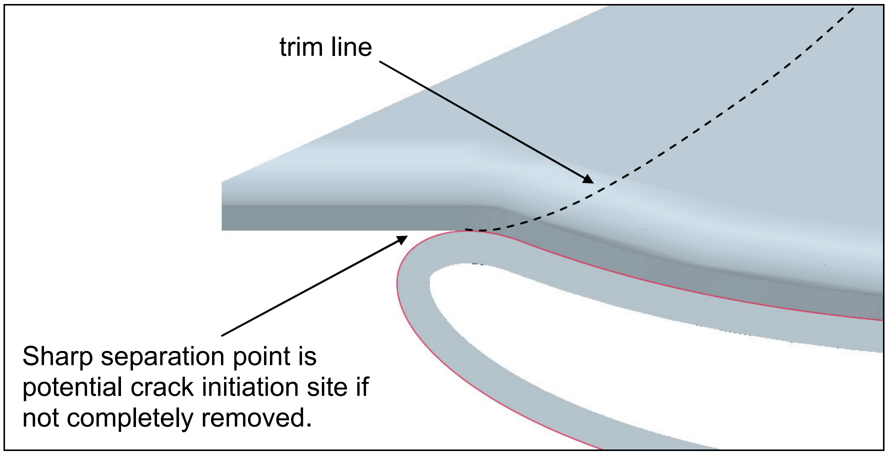

Figure 3.14: Initial idea for excess bracket material at leading edge

After considering many configurations for the excess material and trim line at the leading edge of the brackets, it was decided to eliminate the excess material that separates from the leading edge (Figure 3.15). Although some excess material was left on the bracket leading edge, there was none at the point of contact with the airfoil. As a result, precise preforming in this region would be required but this was a worthwhile trade-off to eliminate a possible crack initiation site and greatly simplify the mould.

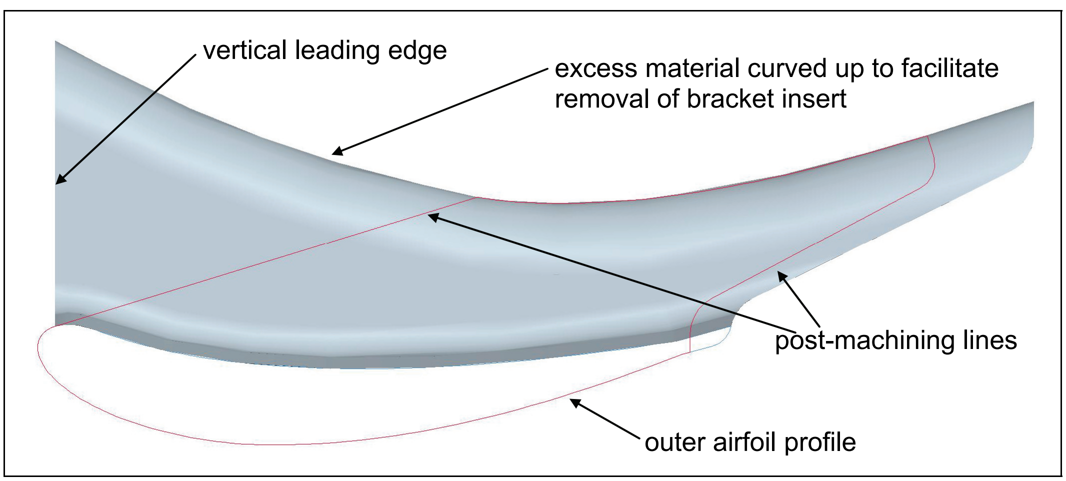

Figure 3.15: Final profile of as-moulded bracket

It will also be noticed from Figure 3.15 that the leading edge of the bracket was made vertical and the trailing edge follows a somewhat complex curve that begins and ends vertically. Both these profiles were selected based on machining considerations. The metal inserts required to fit inside the brackets were not only small, but also consisted of many complex curved surfaces as dictated by the slat design constraints. The bracket profiles had to be carefully selected to avoid any undercuts or sharp, fragile edges. Some general concerns and lessons learned about machining the mould are presented in a separate section below. In addition to machining considerations, the top of the excess bracket material on the leading edge side was curved upward slightly to ease removal of the full bracket insert.

3.8.3 Expanded airfoil trimming

Both ends of the airfoil were also free edges that had to be extended with excess material to be trimmed off in post-machining. This resulted in another separation point at the blended half bracket (Figure 3.16). As mentioned above, the airfoil was expanded here to avoid a separation point. However, when excess airfoil material is added, the separation returns. After more design iterations, the best solution obtained was to have the airfoil material separate perpendicularly from the bracket surface. At this angle, the excess material would be easier to trim without damaging the bracket. Although the airfoil material would become highly distorted during preforming, this distorted region would be trimmed off in post-machining.

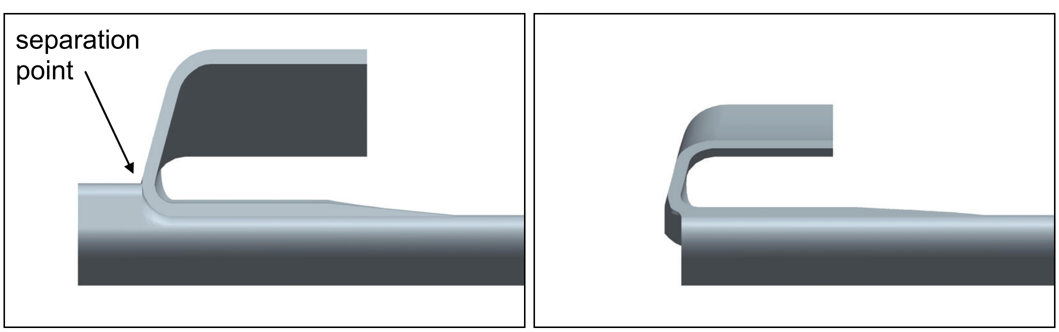

Figure 3.16: Blended half bracket and expanded airfoil before and after post-machining

3.9 Mandrel design

The design of the slat required a hollow airfoil. Two options existed for filling this space in the mould: a mandrel or a bladder. The bladder has the advantage of accommodating a variety of thicknesses and is easy to remove. However, it limits the injection pressure and requires passing an air line into the mould. A solid mandrel might be difficult to remove but would be easier to preform onto, would give a better surface finish, and would simplify the mould. An idea was proposed for the prototype mould to use an aluminum mandrel. Since aluminum has a larger coefficient of thermal expansion than steel, this would make it easier to demould from the part after cooling. In addition, aluminum is easier to machine. If the solid mandrel did not work, the mould could be modified to accommodate a bladder instead.

The aluminum mandrel was the most difficult part to machine because it was long, thin, and fragile. Its small cross section also meant that the amount of thermal expansion would be small. The blended bracket with expanding airfoil also led to a complex shape at one end of the mandrel (Figure 3.17). If this design were adopted on the full size slat, the mandrel would have to be split in two so it could be removed from either end.

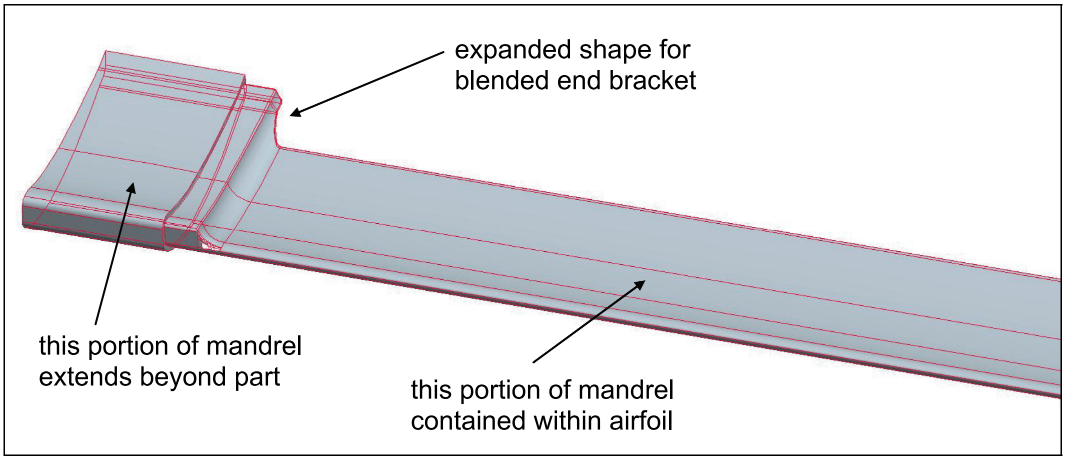

Figure 3.17: Aluminum mandrel for prototype

In addition, designing the mandrel to exactly fill the space within the airfoil would have given a very sharp and fragile trailing edge to the mandrel so this edge was rounded off (Figure 3.18). The resulting space at the trailing edge could be filled with unidirectional fibres which would not only avoid having a resin rich area, but might also help with the structural integrity of the slat. Span-wise fibres were placed at the trailing edge of another composite slat at BHTC to "stabilize" this edge [34].

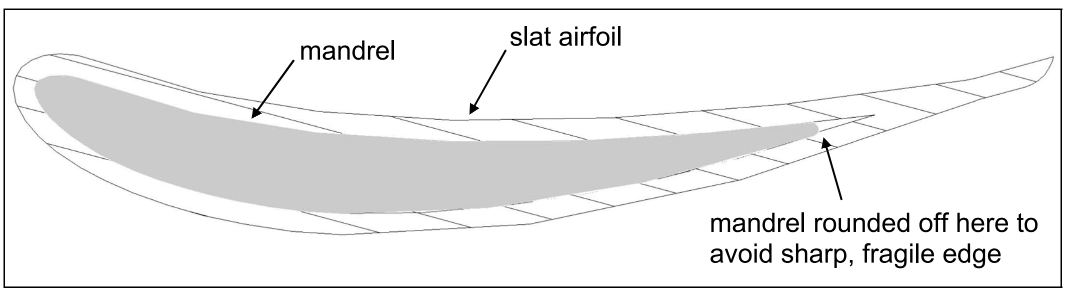

Figure 3.18: Mandrel and slat airfoil cross section

3.10 Machining the mould

Manufacturability of the composite part has thus far been the focus of this chapter. However, the manufacturability of the mould itself was also important.

The mould was machined from steel and aluminum blocks and this had important implications throughout the part and mould design process. A list of some of the more important issues to bear in mind for machinability of the mould is as follows:

- Minimize the number of mould pieces.
- Consider the machining setup for a piece.

  Setup time is generally the most time consuming and labour intensive step in the machining process. Therefore, minimize the number of times a piece must be repositioned for machining. Ideally, try to make it possible to machine everything from one side of the piece. Also, bear in mind that the piece must be somehow fixed during machining. Flat surfaces are convenient for clamping and as machining references. Pieces susceptible to excessive deflections from the machine tool will require additional support (for example long thin pieces such as the mandrel in this project).
- Avoid sharp external edges as they are susceptible to breakage during machining and mould handling.
- Internal edges should usually be avoided.

  Internal corners (3 surfaces intersecting) are impossible to machine without some radius and are difficult to clean. Internal edges (2 surfaces intersecting) can be easier to clean than rounded ones by using a pick, but they require changing to a flat machine tool.
- Internal radii should be carefully selected.

  Standardize internal radii to minimize the number of tool sizes required (9.5 mm (3/8") was used as much as possible for this project). Avoid small internal radii as these require changing to a small tool which is slower and more susceptible to wear and breakage.

This list represents an ideal that will lead to machining efficiency. However, with enough time and money, almost anything can be machined. There are cases where machining complexity is either necessary or offset by some benefit elsewhere in the project. For this project, it was not possible to avoid certain difficult machining steps. For example, the airfoil shape contains radii as small as 2.3 mm (0.09") that cannot be changed. Combined with the long length of the airfoil, particularly on the full-size slat, this presents an unfortunate but necessary machining challenge.

However, a number of decisions and changes were made to facilitate machining. As mentioned above, the side profile of the brackets was carefully selected to avoid undercuts and sharp edges. Also, the literature suggests using an angled parting plane with sharp edges for moulding round shapes such as the airfoil to minimize accidental fibre pinching as the mould closes [15] (Figure 3.19). Although this was at first considered, in the end the parting plane was made flat to simplify machining of this already difficult to machine prototype mould. If fibre pinching proved to be a problem in the prototype trials, the modified parting plane design would be recommended for the full-size mould.

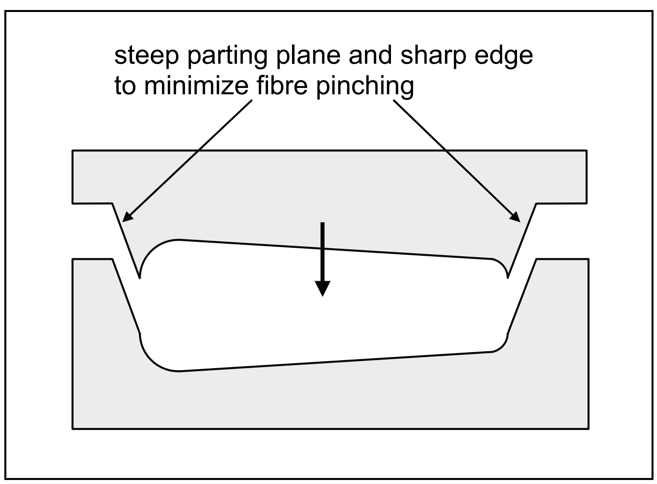

Figure 3.19: Possible mould design to minimize fibre pinching

[15]

3.11 Alternate slat design

During the design of the prototype slat and mould, a new and somewhat more radical design for the slat was proposed. The traditional design was essentially the same as the existing metal design with various minor modifications. The new design represented a more fundamental redesign from a composite material perspective. It consisted of continuous braided material that was pinched together at the bracket locations (Figure 3.20). The result was a slat with truly integrated brackets and many advantages.

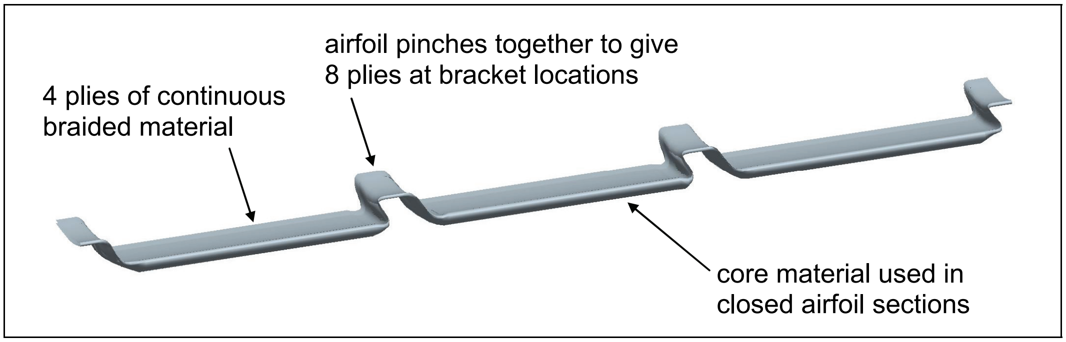

Figure 3.20: Alternate design proposed for the slat

From a stress analysis perspective, having the brackets formed continuously from the airfoil material was ideal. In addition, if the airfoil was made with four plies as proposed in the stress analysis, the brackets would have a substantial thickness of eight plies. Although no stress analysis was performed on this design, it seems likely to be more compliant than the traditional design both axially and in bending since the airfoil is essentially divided into three sections. Dividing the slat airfoil into three section was actually the strategy attempted with the latest metal design to reduce stresses in the brackets due to stiffness in bending. Axial loading could also become an issue if the composite slat has a different coefficient of thermal expansion than the horizontal stabilizer, for example if these two components were made of different materials.

This alternate design also has a number of advantages from a manufacturing perspective. There are no more "trapped" regions under the brackets requiring small inserts. A more simple two-piece mould design could therefore be used. Since the hollow portions of the airfoil would be closed, these would have to be filled with some type of core. Post-machining would be reduced to simply trimming the excess material at either end of the slat. Braided material is quite versatile because it can be elongated or shortened in preforming to give the desired circumference in the airfoil sections and the desired flat width in the brackets. The question that remains is whether it could deform enough to capture the significant backward slant required for the bracket sidewalls.

Finally, perhaps one of the biggest cost-saving advantages of this design is the ease of installation. In the traditional design the fastener locations for attaching the slat to the horizontal stabilizer are obstructed by the slat airfoil. This requires drilling holes through the airfoil in order to access the fasteners. With the new design, all fastener locations are fully accessible.

There is, however, one critical disadvantage with the new design. A portion of the airfoil at each bracket location is lost. It could be argued that the amount lost is small and occurs only at bracket locations where the airflow would most likely be disturbed anyway. However, it does represent a divergence from the current "tried and true" design. As such, this new design was sidelined in favour of the more traditional design in order to avoid re-analyzing the aerodynamic behaviour of a new configuration.

3.12 Final prototype slat and mould design

A solid model of the final prototype part design indicating excess material that would be removed in post machining is shown in Figure 3.21. Solid models of the mould inserts as well as the preforming and mould assembly sequence are shown in Figure 3.22. The mould inserts for the prototype consist of a lower insert, upper insert, and two bracket inserts all made of P20 tool steel. There is also an aluminum mandrel that fits inside the hollow slat airfoil.

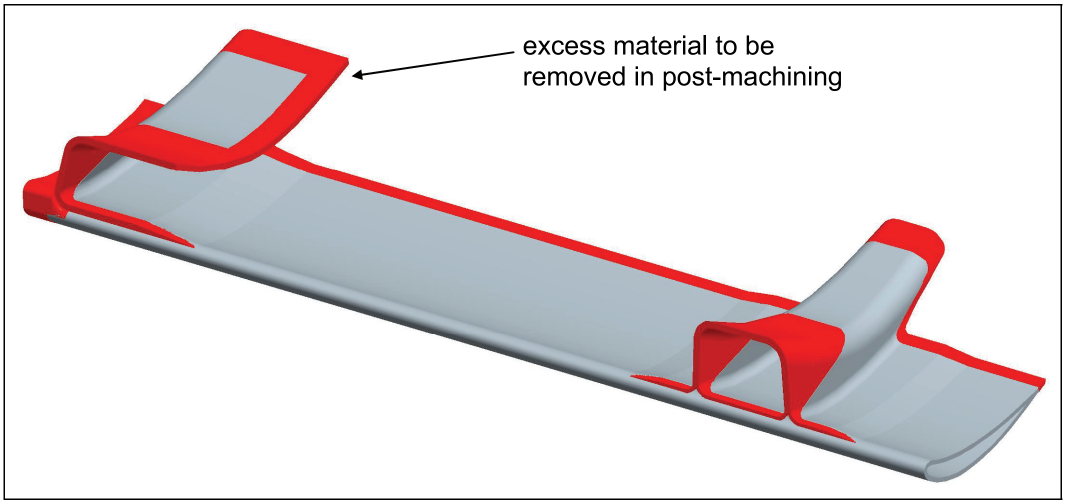

Figure 3.21: Final prototype slat design

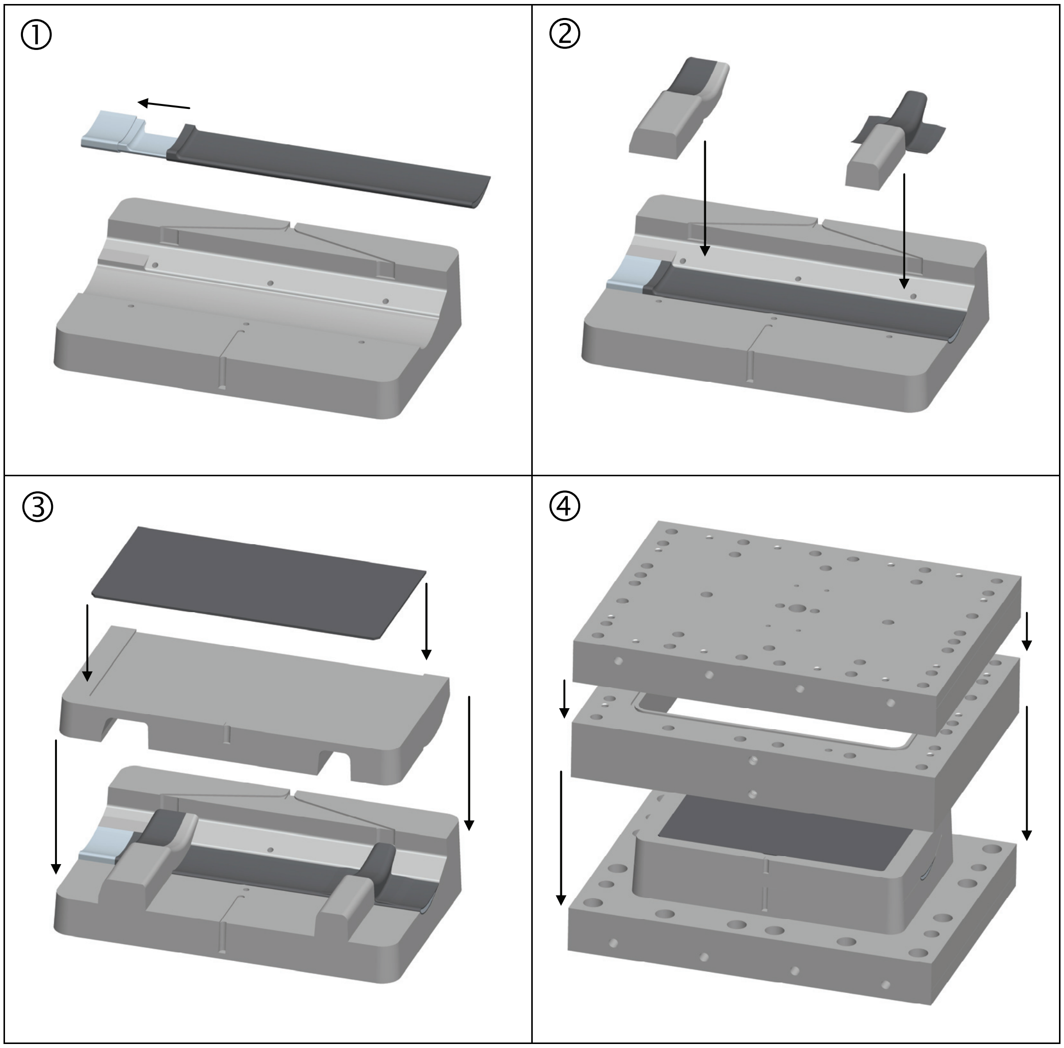

Figure 3.22: Mould inserts and assembly sequence

The preforming sequence begins by laying up the airfoil fabric around the mandrel and placing this into the lower insert. The brackets are then laid up around their respective inserts and placed onto the airfoil. The bracket inserts are fastened to the lower insert to ensure correct positioning and to hold them in place during demoulding. After placing the upper insert over the part, a witness coupon plate is positioned in a recess on top of the upper insert. This coupon can be used for quality control of the manufacturing process. Finally, the mould cavity is closed around the inserts and the part is ready for injection. See Appendix B for photographs of the actual preforming process.

3.12.1 Injection strategy

As mentioned above, mould filling simulations were carried out by École Polytechnique de Montréal throughout the design process. Based on the results of these analyses and the existing mould design constraints, the injection strategy selected was to inject the part in the chord-wise direction, beginning from the trailing edge and venting from the leading edge (Figure 3.23).

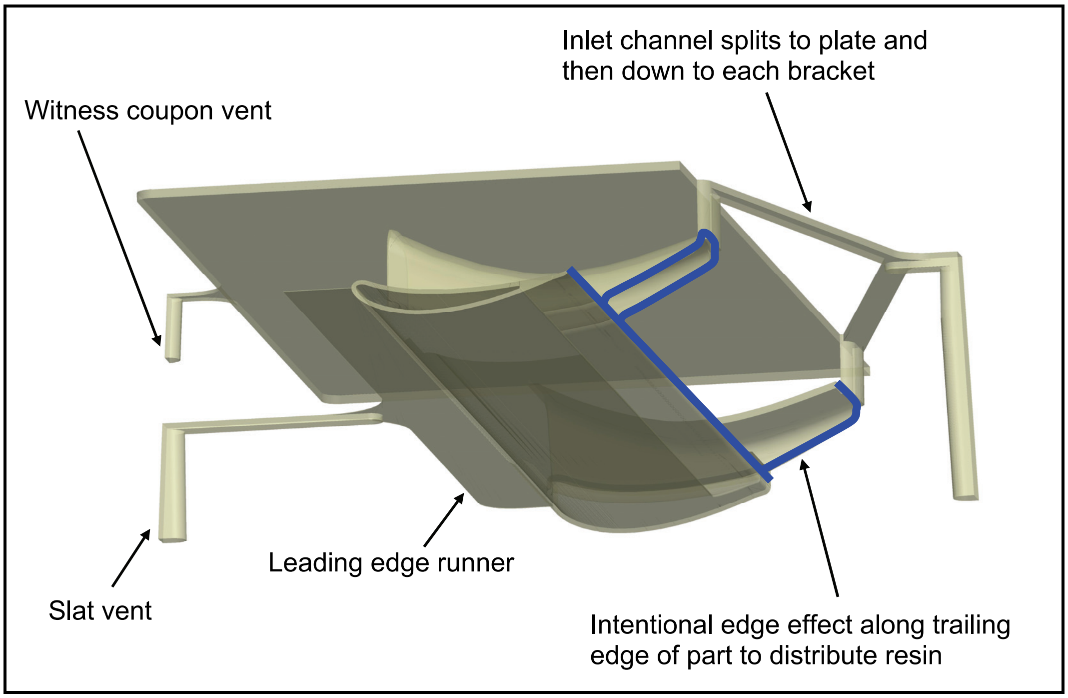

Figure 3.23: Prototype mould cavity to be filled

In the prototype mould design, a single resin inlet was split in two to arrive at the upper trailing edge of each bracket. An edge effect was intentionally created along the entire trailing edge of the part to act as a runner and distribute resin quickly along the length of the part. A 0.25 mm (0.010") thick runner was machined into the mould at the leading edge of the airfoil to collect the resin into a single vent port. The resin channels feeding the part were also split to provide resin to the witness coupon. Since the filling time for the part and plate were expected to be different, a separate gate was provided for the plate.

3.12.2 Mould sensors

To gain additional insight into the mould filling and cure process of the prototype part, a number of sensors were added to the mould. Six holes already existed through the base of the mould cavity. Therefore, in the final mould design, the position of the part was adjusted so that three of these holes, when extended through the lower insert, would arrive at the leading edge runner (Figure 3.24). This would leave the other three to arrive slightly behind the trailing edge of the slat. These six holes were added to the lower insert with threads and dimensions such that temperature or pressure probes could be installed in any of them. In addition, a dielectric sensor was added through the top of the mould cavity where it would arrive at the witness coupon.

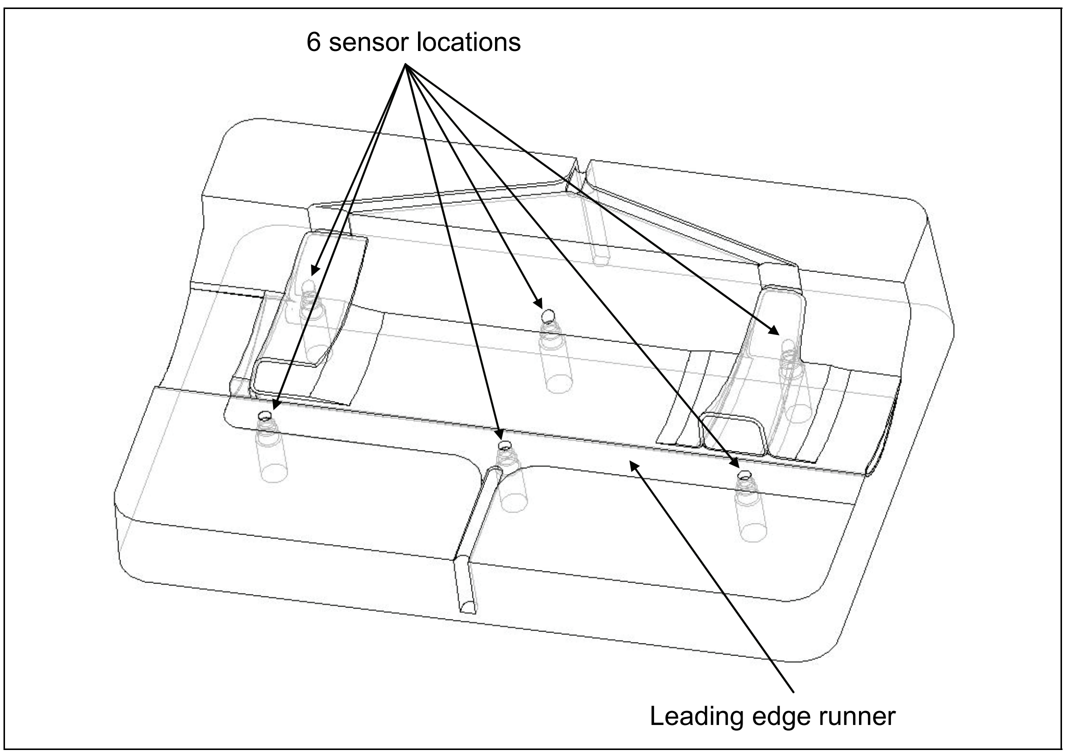

Figure 3.24: Six sensor locations in lower insert

3.12.3 Thermal shrink factors

As mentioned previously, thermal expansion of the mould and part during cure must be accounted for in the mould design to ensure the correct final part dimensions are obtained. This can be done using finite element analysis, or more simply with a shrink factor. For this project, a shrink factor of 0.9985 was applied to all the mould dimensions. The value for this factor was obtained experimentally during a previous RTM project carried out by Delastek, AMTC, and BHTC using the same resin and fabric for the part and the same tool steel for the mould [35]. In this previous effort, a part was first made without applying any shrink factor. Comparing the resulting part dimensions with the design dimensions gave the factor of 0.9985. This factor therefore accounts for both the expansion of the mould components during cure at 180ºC as well as the subsequent contraction of the part when cooled back to room temperature.

For the current project, aluminum was used for the mandrel which required an additional shrink factor due to its even higher coefficient of thermal expansion. This additional factor was determined as follows [36].

At the cure temperature, corresponding dimensions on the aluminum mandrel and steel mould must be equal:

$$L_{Al} + L_{Al} \cdot CTE_{Al} \cdot \Delta T = L_{P20} + L_{P20} \cdot CTE_{P20} \cdot \Delta T$$

where L_{Al} is a dimension of the aluminum mandrel at room temperature

L_{P20} is the corresponding dimension of the steel mould at room temperature

CTE_{Al} is the coefficient of thermal expansion of aluminum:

23.6 um/mºC [37]

CTE_{P20} is the coefficient of thermal expansion of P20 tool steel

12.8 um/mºC [37]

ΔT is the difference between room temperature and cure temperature:

180ºC - 20ºC = 160ºC

Solving for the aluminum mandrel dimension with respect to the steel mould dimension at room temperature gives:

$$
\begin{aligned}
L_{Al} &= L_{P20}\left(\frac{1+CTE_{P20}\cdot\Delta T}{1+CTE_{Al}\cdot\Delta T}\right)\\
&= L_{P20}\left(\frac{1+12.8\cdot 10^{-6}\cdot 160}{1+23.6\cdot 10^{-6}\cdot 160}\right)\\
&= L_{P20}\cdot 0.998
\end{aligned}
$$

Therefore, after applying the experimentally obtained shrink factor for tool steel of 0.9885 to all mould components, including the mandrel, this additional shrink factor of 0.998 was applied to the mandrel to account for the greater thermal expansion of aluminum.

3.13 Summary

A half-length prototype slat and mould were designed. These designs were carried out taking into consideration results from stress analysis and flow modelling as well as manufacturability requirements. The prototype slat includes two different bracket designs and the mould consists of a new set of metal inserts to be placed within a pre-existing RTM modular mould cavity. These inserts were machined by Delastek after which manufacturing of prototype parts was begun at AMTC.

Chapter 4 Prototype manufacturing trials

4.1 Introduction

Prototype slat manufacturing began in the spring of 2007. At the time of writing, eight prototypes had been produced (001-008). The goal of these prototype manufacturing trials was to demonstrate the process and to locate and resolve any potential issues before proceeding to the full size slat. As a result, the manufacturing procedure was modified and improved with each prototype produced. Section 4.2 provides an overview of the general manufacturing procedure while section 4.4 provides details about the improvements made to the procedure. Injection log files and charts of the sensor data collected during the injection and cure cycles of each part are provided in Appendix A. Appendix B contains a selection of photographs from the manufacturing trials.

4.2 General manufacturing procedure

4.2.1 Mould preparation

Upon receipt of the mould inserts from Delastek, all mould surfaces in contact with the part were polished (Figure 4.1). This was followed by a thorough cleaning with acetone. Mould sealer (Loctite® Frekote® B-15 Mold Sealer) and release agent (Loctite® Frekote® 700-NC Mold Release Agent) were then applied following the manufacturer's directions to any surface of the mould that might come into contact with resin. If any damage occurred to critical mould surfaces during part manufacturing, these surfaces were re-polished and treated. The mould cavity and any holes within the cavity were sealed with o-rings.

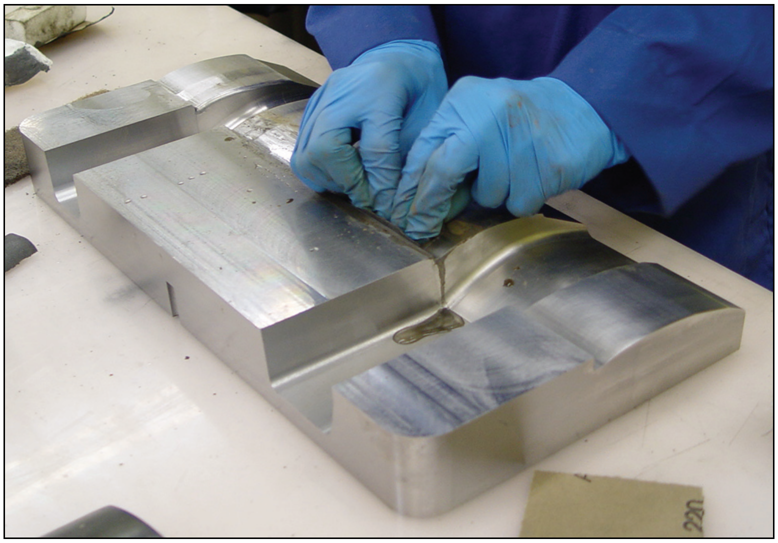

Figure 4.1: Polishing upper mould insert

4.2.2 Preforming

Preforming was carried out by hand directly on the mould inserts (Figure 4.2). The fabric used was pre-impregnated with a small amount of resin which made it tacky on one side. For prototypes 001 to 004, pre-cut rectangles of fabric were placed on the inserts and then cut down to size by hand. For subsequent prototypes, exact fabric patterns were digitized and cut using an automatic cutting table (Eastman M9000). These pre-cut plies could be placed onto the inserts without any manual trimming required.

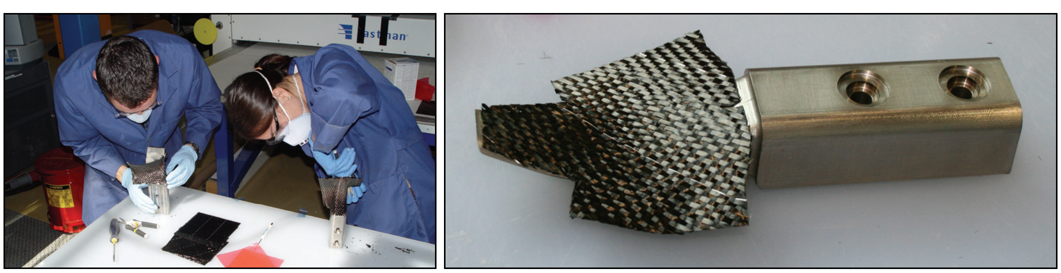

Figure 4.2: Preforming with pre-cut rectangles (left) and exact patterns (right)

For the airfoil, plies were wrapped around the mandrel with a ply dropoff included at the trailing edge (Figure 4.3). In most cases, tows of unidirectional fibre were placed along the trailing edge of the mandrel to help fill the ply dropoff region.

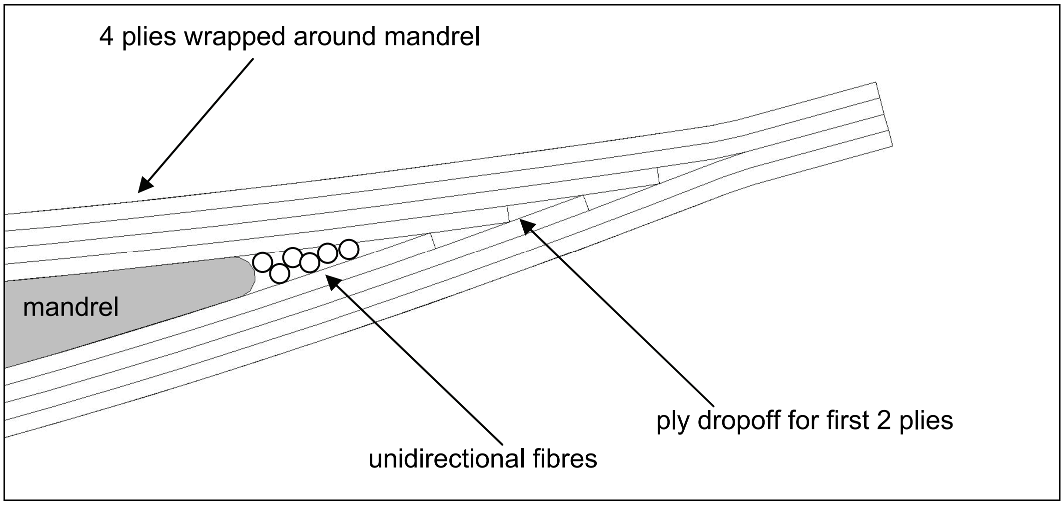

Figure 4.3: Airfoil fibre positioning

For the full bracket, three plies were wrapped around the full bracket insert (Figure 4.4). The ends of each ply met at butt joints which were staggered along the lower surface of the insert. The remaining three plies were wrapped over the insert and bent outward to form the two outer flanges. Ply dropoffs were measured onto these flanges using the taper machined in the upper insert as a reference. Finally, tows of unidirectional fibre were again used to fill the triangular space left at the two T-junctions.

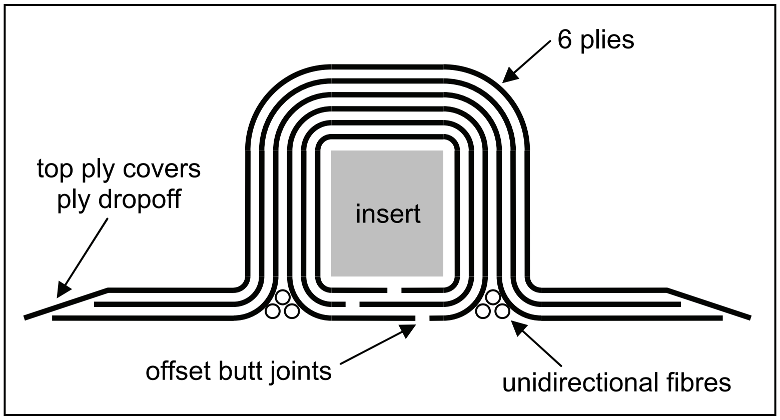

Figure 4.4: Full bracket fibre positioning

For the half bracket, all six plies were simply wrapped around the insert (Figure 4.5). The ply dropoff for this bracket could be measured using the taper machined into the bracket insert itself.

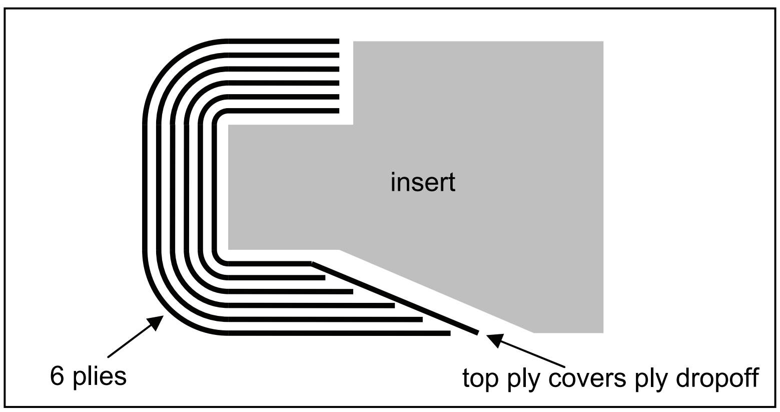

Figure 4.5: Half bracket fibre positioning

Special care was taken to ensure a sufficient space was left along the leading and trailing edges of the preform to create a runner effect as required by the mould filling strategy (Figure 4.6). All part edges along which preferential flow was not desired, that is all edges aligned with the direction of flow, were filled in with expanded PTFE joint sealant. These edges would be removed in post-machining.

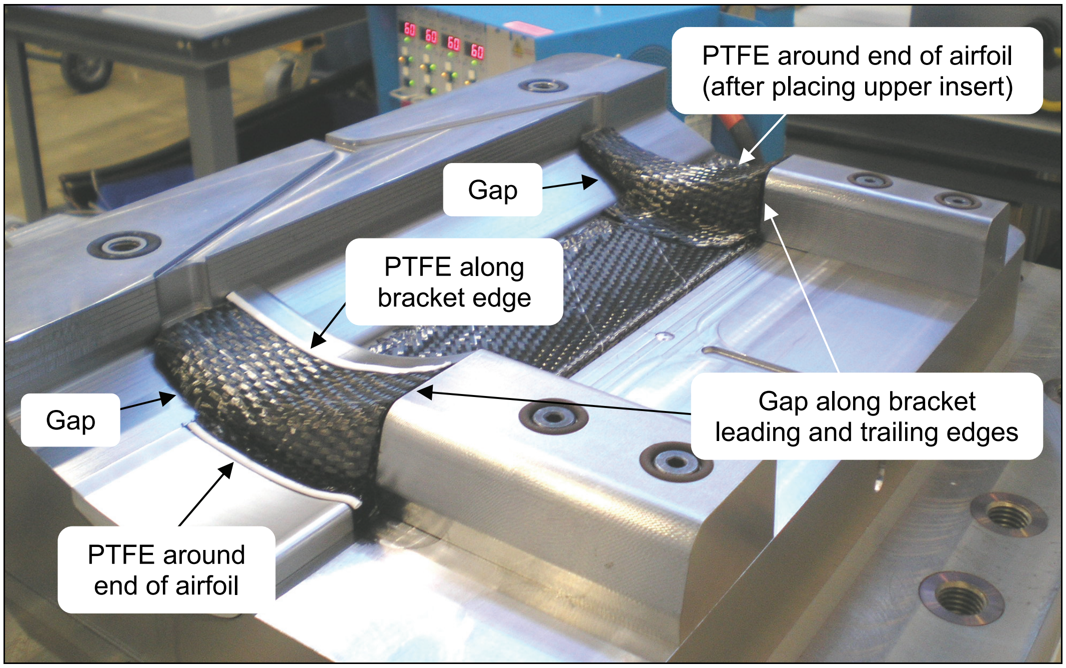

Figure 4.6: Preform loaded into mould

4.2.3 Injection preparation

After placing the preform in the mould and closing the cavity, the injection hardware was installed (Figure 4.7). A pressure pot was connected to the inlet, and a catch pot with vacuum line was connected to the two outlets. A catch pot is important to prevent resin from entering the vacuum pump [18]. Clear tubing was used in order to monitor the flow into and out of the mould. A valve was placed on each outlet line to allow individual flow control in the part and witness coupon. After the first two injections, a valve was also added to the inlet. The resin was preheated to 80ºC before the injection as suggested by the manufacturer. For prototypes 001 to 004, the mould was preheated to 100ºC. For all subsequent prototypes, the mould was preheated to the cure temperature of 180ºC.

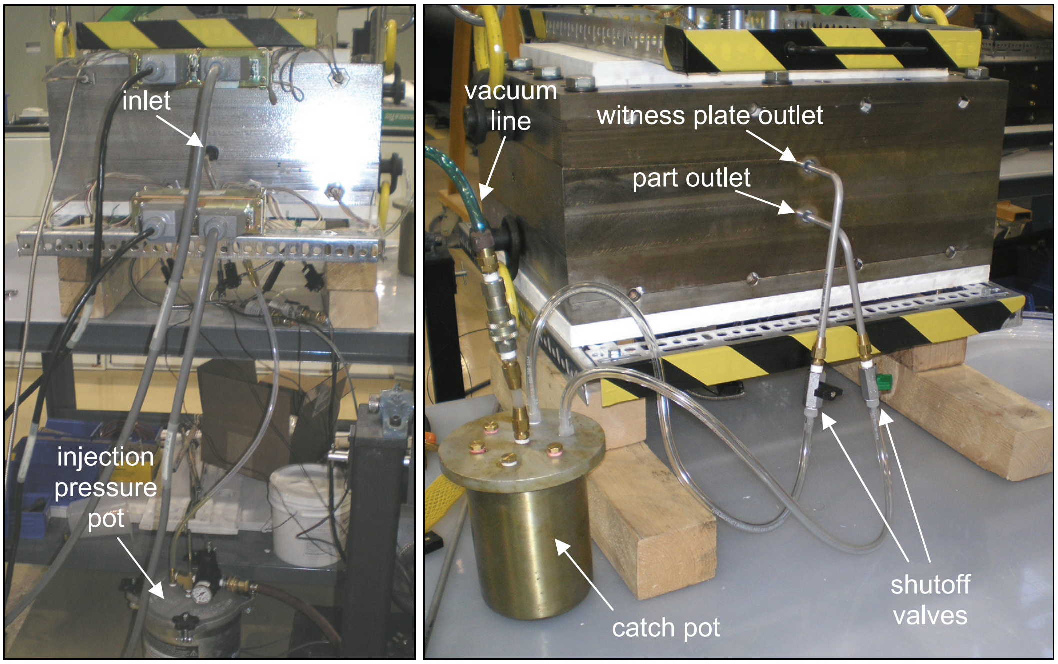

Figure 4.7: Injection setup

A vacuum leak test was performed before each injection. Pressure and temperature sensor data from the mould were collected using a computer data acquisition system. Mould heater cartridge temperatures, injection pot pressure, and significant events were entered manually into the data acquisition program using time-stamped notes.

4.2.4 Injection

Vacuum pressure up to a maximum of 25 mmHg was applied to the mould outlet. Due to the small size of the part, positive injection pressure was generally not required for resin to fill the mould. Exact values of vacuum and injection pressure were varied from part to part as the procedure was refined. Filling times ranged from 2 to 9 minutes. Resin leaving the mould generally contained air bubbles at first. At this stage, the outlet valves were periodically opened and closed for typically 5 to 10 minutes. Once no bubbles were visible in the resin leaving the mould, the outlet was closed for the remainder of the process. This process of bleeding resin from the mould is recommended for liquid composite moulding processes to minimize voids and dry spots in the part [9].

After filling the part and closing the vents, the injection pot pressure was generally ramped up to 280 kPa (45 psi) which was the limit for the pressure pot being used. Increasing the resin pressure after filling has been found to improve part properties [38]. Starting with prototype 003, a valve was added to the inlet line which isolated the pressure pot from the mould and allowed pressure to build up in the mould to even higher levels, in some cases in excess of 690 kPa (100 psi).

For prototypes 001 to 004, for which the mould was preheated to 100ºC, the mould temperature was ramped up to 180ºC at roughly 1ºC per minute after mould filling. This was done by manually increasing the mould cartridge temperatures by 10ºC every ten minutes. Generally, the part temperature as measured by the sensors in the mould was found to lag behind the cartridge temperatures by about 20ºC during the ramp up. Toward the end of the ramp, the cartridge temperatures were increased to 190ºC to help maintain the desired ramp rate. They were then brought back to 180ºC as the part temperature passed 170ºC to avoid any overshoot. Once the part temperature reached 180ºC, the two hour soak period was begun.

4.2.5 Demoulding

For prototypes 001 to 005, the mould was allowed to cool overnight to 100ºC before demoulding. Subsequent prototypes were demoulded immediately after the soak period with the mould still at the cure temperature of 180ºC.

A screw jack in the lid of the mould cavity was used to lift the cavity while pushing down on the inserts. This prevented the inserts from lifting with the cavity and possibly damaging the part. Due to the careful mould surface preparation, the part and resin flash generally separated easily from the mould. The part and all mould inserts could be easily separated by hand except for the mandrel.

For the mandrel, a mandrel extractor was designed and built at AMTC (Figure 4.8). It consisted of a screw jack mounted to the side of the mould which pulled on an eye bolt screwed into the end of the mandrel. The setup was quite effective and able to remove the mandrel without excessive force. However, during each extraction the mandrel was scratched along its length. This required the mandrel to be re-polished and surface treated between each injection. For prototypes 006 to 008, the part and mandrel were placed in a freezer for several hours before extraction, with the hope that the higher coefficient of thermal expansion of aluminum would make it easier to remove the mandrel. However, damage to the mandrel was no less for these trials than for the previous cases.

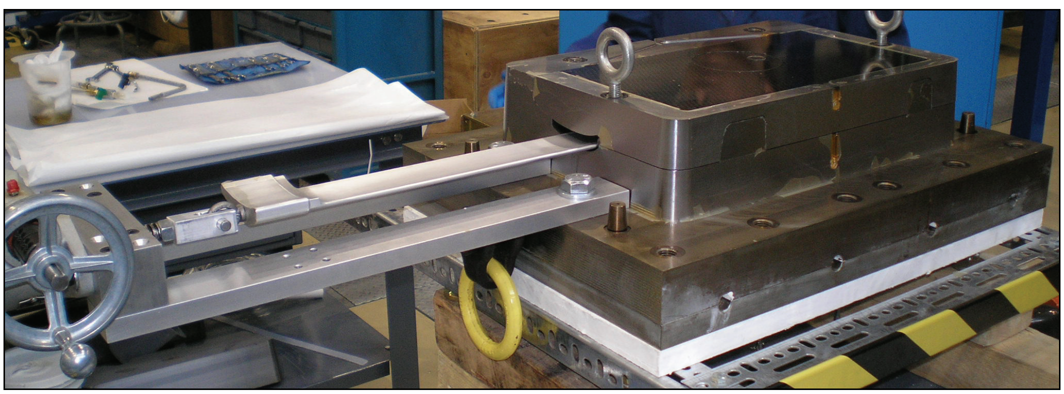

Figure 4.8: Aluminum mandrel being extracted from part

4.2.6 Post-machining

Post-machining of excess material on prototype 001 was carried out using a handheld vibrating cutting tool (Figure 4.9). Final part shaping was done with a small rotary sanding tool. There were no major difficulties with this stage except that it was highly operator dependent and would therefore be difficult to produce consistently trimmed parts. No other prototypes parts had been trimmed at the time of writing.

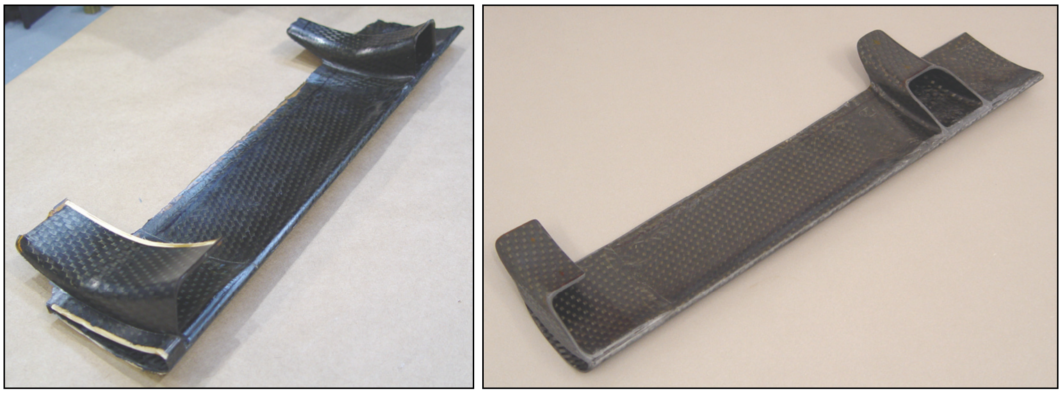

Figure 4.9: Prototype as removed from mould (left) and after trimming (right)

4.3 Prototype manufacturing results

4.3.1 Overview

Table 4.1 provides a brief summary of the eight prototype parts manufactured at the time of writing. Injection log files for each part are provided in Appendix A.

Table 4.1: Summary of prototype manufacturing trials

Prototype 001	20 March 2007
- all fabric cut by hand - no ply dropoff at trailing edge - no vacuum applied because of high leak rate in mould - small amounts of resin leaked at sensor locations and inlet line	
Prototype 002	26 April 2007
- o-ring groove added to lower insert base to seal off sensor holes - temperature sensors threaded to clamp lower insert in place - cutting table used to cut well aligned rectangular fabric patterns - ply dropoff measured on airfoil trailing edge (this was done for all subsequent prototypes) - layup sequence altered to have ±45 plies on outside of brackets in an effort to reduce fibre washout at bracket ply dropoffs (done for all subsequent prototypes) - new sensor sealing strategy - small resin leak from one of the sensors	
Prototype 003	23 May 2007
- new sensor sealing strategy again (sensors left in place for all subsequent prototypes) - valve added to inlet line	
Prototype 004	24 May 2007
- demoulding of 003 and injection of 004 done in the same day - upper surface of mould heated faster than lower which improved surface finish by reducing the temperature gradient at the location of the part	

Prototype 005	20 June 2007
- exact preform patterns cut on automatic cutting table (used for all subsequent prototypes) - added one layer to airfoil (5), lengthened ply dropoffs, added considerably more unidirectional filler material which eliminated fibre washout at bracket ply dropoffs (used for all subsequent prototypes) - preheated mould to 180ºC before injecting (done for all subsequent prototypes) - some injection problems (resin cooled before injection while waiting for mould to heat, outlet hose melted shut and had to be replaced during injection)	
Prototype 006	30 July 2007
- loaded mould, injected, and demoulded at 180ºC (done for all subsequent prototypes) - started new batch of resin - because of high temperature and new resin, viscosity was lower than usual and resin went through mould very quickly - ran out of resin in injection pot allowing air to enter part resulting in the poorest quality prototype produced	
Prototype 007	31 July 2007
- resin injected using gradually increasing vacuum pressure to give a slower resin flow speed (used for all subsequent prototypes) - two leaks in the injection line required reducing injection pressure to 70 kPa (10 psi) and leaving injection pressure pot connected for entire cure	
Prototype 008	2 August 2007
- new hardware setup to eliminate leaks - compressed air line attached to inlet after filling, pressure in mould ramped up to 690 kPa (100 psi) - best surface finish of all parts to date	

4.3.2 Material and time requirements

Some statistics about the manufacturing process are as follows:

- Resin usage was measured to be less than 350 mL (12 US fl. oz.) for each of prototypes 007 and 008.
- After creating exact preform patterns and nesting them onto a roll 1.07 m (42") wide, a length of 1.61 m (63.2") was required per prototype, including the witness coupon
- Before creating exact preform patterns, the three prototype components (2 brackets and 1 airfoil) required approximately1 hour each to preform, resulting in a total of 3 operator hours for preforming. After creating the exact preform patterns, the time was reduced to 20-30 minutes per component for a total of under 1.5 operator hours.
- Exact times were recorded for prototype 007 as follows: 20 min. for airfoil preform, 22 min. for half bracket preform, 30 min. for full bracket preform, 18 min. for plate preform. With two operators, the total working time from the start of preforming until opening the injection valve (preforming, loading the preform, closing the mould, installing injection hardware, conducting vacuum leak tests) was 154 minutes (2.6 hours).
- Parts were made with a turnaround time of 1 day on two occasions. However, these were long days that were more representative of 2 regular working days. Under optimal conditions, it is predicted that parts could be made with a turnaround time of well within 1 regular working day.

4.3.3 Sensor data

Pressure and temperature data were collected for each prototype part produced. Graphs of this data are shown in Appendix A. Included on these graphs are the predicted development of degree of cure, viscosity, glass transition temperature, volumetric chemical shrinkage, and modulus. The models used for these predictions are as follows [39].

Cure kinetics model:

$$\boxed{\frac{\partial \alpha}{\partial t} = A \exp\left(\frac{-Ea}{RT}\right)\frac{\alpha^m (1-\alpha)^n}{1+\exp\left[C\left(\alpha-\left(\alpha_{C0}+\alpha_{CT}T\right)\right)\right]}}$$

where

A	58528.26
Ea	68976.25
m	0.630303295
n	0.604508188
C	15.62774321
α_{C0}	-0.901960155
α_{CT}	0.003919833

Viscosity model:

$$\mu = \mu_1(T) + \mu_2(T)\left(\frac{\alpha_{gel}}{\alpha_{gel}-\alpha}\right)^{\left(A+B\alpha+C\alpha^2\right)}$$

$$\mu_i(T) = A_i \exp\left(\frac{E_i}{RT}\right) \quad i = 1 \text{ or } 2$$

where

A_1	9.80795E-19
E_1	115305.2076
A_2	0.006417886
E_2	12084.43542
A	0.05
B	1
C	3
α_{gel}	0.681639816

Glass transition temperature model:

$$\boxed{\frac{Tg - Tg_0}{Tg_\infty - Tg_0} = \frac{\lambda\alpha}{1-(1-\lambda)\alpha}}$$

where

Tg_0	-14.23
Tg_∞	213.75
λ	0.396

Volumetric Chemical Shrinkage:

$$\boxed{VS = \begin{cases} 0 & \text{for } \alpha < \alpha_{gel} \\ A\cdot\alpha + B & \text{for } \alpha \geq \alpha_{gel} \end{cases}}$$

where

A	14.95452258
B	-10.94281551
α_{gel}	0.681639816

Tensile modulus model:

$$E = \begin{Bmatrix} 0 \\ E_1 \\ E_2 + (E_1 - E_2) \cdot \left(\dfrac{T - T_2}{T_1 - T_2} \right) \\ E_3 + (E_2 - E_3) \cdot \left(\dfrac{T - T_3}{T_2 - T_3} \right) \\ A \cdot \exp\left(-K \cdot T^* \right) \\ E_4 \end{Bmatrix} \quad \begin{Bmatrix} \alpha < \alpha_{gel} \\ T_1 > T^* \\ T_1 < T^* < T_2 \\ T_2 < T^* < T_3 \\ T_3 < T^* < T_4 \\ T_4 < T^* \end{Bmatrix} \quad \text{where}$$

α_{gel}	0.681639816
T_1	-168
T_2	-30
T_3	-15.17967922
T_4	10
E_1	3200000000
E_2	1900000000
E_3	1110682860
E_4	13000000
A	80000000
K	0.172

The results of the sensor data and models were generally as expected. Mould temperature at the part location lagged behind the heater cartridge temperatures by about 20-30 minutes. Resin pressure in the mould matched that in the pressure pot. When the outlet valves were opened during mould "burping", drops in pressure were observed. When the inlet and outlet valves were closed, pressure was observed to increase during temperature ramp-ups due to the thermal expansion of the resin. However, upon resin cure, the measured mould pressure dropped as the shrinking resin pulled away from the sensors. This pressure drop correlated well with the cure models. Predicted gelation is indicated by the sharp increase in resin viscosity, after which modulus, glass transition temperature, and volumetric chemical shrinkage begin to develop.

4.3.4 Fibre volume fraction

For prototype 008, weight measurements were taken of the fabric preform before injection and of the part after cure. Based on these measurements and the specified material densities, average fibre volume fractions were calculated as shown in Table 4.2.

Table 4.2: Calculation of fibre volume fraction from weight measurements

	Slat	Witness coupon
Weight of fabric (measured)	193g	262g
Fibre density [40]	1.78g/cm^3	
Fabric volume	193 / 1.78 = 108cm^3	262 / 1.78 = 147cm^3
Weight of cured part (measured)	259g	376g
Weight of cured resin	259 – 193 = 66g	376 – 262 = 114g
Density of cured resin [31]	1.22g/cm^3	
Volume of cured resin	66 / 1.22 = 54cm^3	114 / 1.22 = 93cm^3
Total volume	108 + 54 = 162cm^3	147 + 93 = 240cm^3
Design volume from model	162cm^3	253cm^3
Avg. fibre volume fraction	108 / 162 = 0.67	147 / 240 = 0.61
Design average fibre volume fraction	0.58 (see note below)	0.57

Note: The design fibre volume fraction for the part was 0.50. However, prototypes 005-008 had an extra layer of fabric added to the airfoil. The average design fibre volume fraction is therefore calculated as:

$$\begin{aligned}\text{avg v}_\text{f} &= \text{bracket v}_\text{f} \cdot \frac{\text{bracket vol}}{\text{total vol}} + \text{airfoil v}_\text{f} \cdot \frac{\text{airfoil vol}}{\text{total vol}}\\ &= 0.50 \cdot \frac{55\text{cm}^3}{162\text{cm}^3} + 0.62 \cdot \frac{107\text{cm}^3}{162\text{cm}^3}\\ &= 0.58\end{aligned}$$

These estimates of average fibre volume fraction are higher than the design values. This difference could be attributed to the presence of a small amount of resin pre-impregnated in the fabric which was not accounted for in the above calculations. This resin was added to the fabric by the manufacturer to provide tackiness during preforming

It is recommended that a more accurate measurement of actual fibre volume fraction in the part be made by taking samples from the parts with known masses, burning off the resin, and measuring the remaining fibre mass. Also, a number of cross-sections should be cut from the parts and examined under microscope to determine the void content of the parts produced.

4.4 Manufacturing improvements

The following subsections describe some of the more important improvements that were made to the manufacturing procedure over the course of producing eight prototype slats.

4.4.1 Heat all inlet and outlet resin lines

It was found that resin can cool in the inlet and outlet tubes. The resulting increase in viscosity can hinder mould filling. As a result, these tubes were heated with silicone blanket heaters and also kept as short as possible.

4.4.2 Add o-ring groove to the lower mould insert

Sealing and installing the sensors was found to be quite difficult. A large o-ring surrounding all six sensors was added to the base of the lower insert after prototype 001 to seal this interface (Figure 4.10). To seal the upper end of the sensors, pipe thread sealant tape and expanded PTFE joint sealant was applied to the threads and shoulder of each sensor. Once a good seal was obtained with prototype 003, the sensors were left installed in the mould permanently.

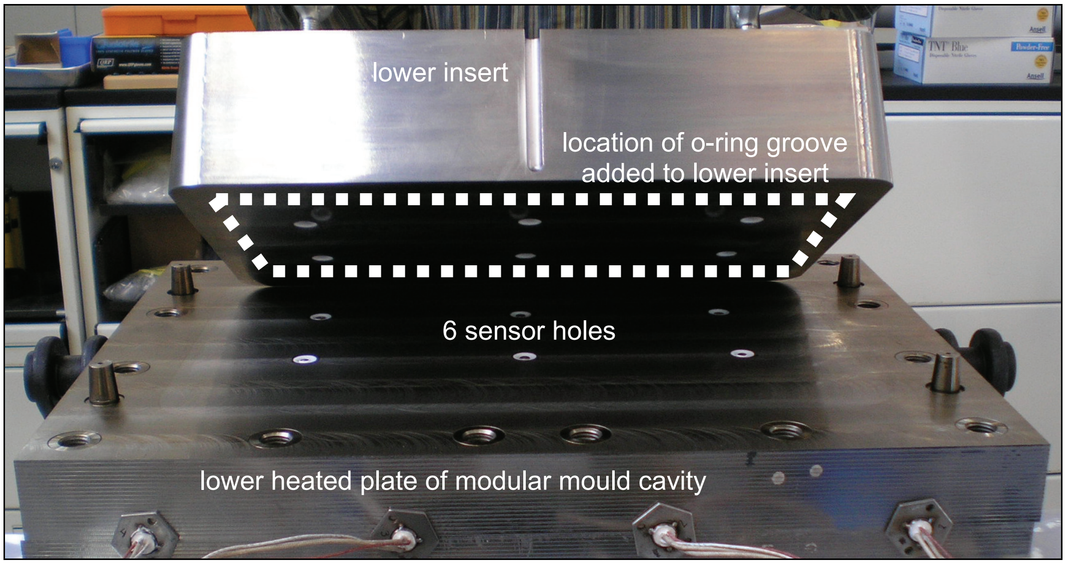

Figure 4.10: Location of o-ring groove added to lower insert

4.4.3 Add inlet shutoff

Starting with prototype 003, a shutoff valve was included in the inlet line. This had two important implications. First, the pressure in the mould could be increased beyond the safety limitations of the pressure pot. The mould was able to withstand pressures in excess of 1.4 MPa (200 psi). However, the pressure pot being used had a much lower rating and was equipped with a safety release valve that limited pressure to ~340 kPa (50 psi). As mentioned above, increasing resin pressure in the mould during the cure can improve part properties.

When the mould temperature is being ramped up, thermal expansion of the resin creates a natural pressure increase in the mould. By simply shutting all resin valves, pressures in excess of 830 kPa (120 psi) were achieved in the mould for some prototypes. However, starting with prototype 005, the mould was preheated to the cure temperature before injecting, so thermal expansion during the ramp up could no longer be used to increase pressure in the mould. This problem was overcome with prototype 008 where the injection hardware was configured such that, after filling the mould and closing all the valves, the injection pressure pot could be disconnected from the mould and replaced with a compressed air line.

With this air line, a pressure of 690 kPa (100 psi) could be applied to the resin in the mould. This system also allowed much more control over the mould pressure than relying on the thermal expansion of the resin to create its own pressure.

The second advantage of adding a shutoff valve to the inlet was that the injection pressure pot could be disconnected from the mould once filling was complete. Filling, including the bleeding stage, takes on the order of 20 minutes while the entire cure cycle can take 2 to 3 hours. Only using the injection apparatus for a short period of time is advantageous in a production environment because the same injector can be used to fill multiple moulds. Even in a non-production environment, only requiring the injection apparatus for a short period of time means it can be cleaned and prepared for the next injection while the part is curing. This also minimizes the amount of time any excess resin in the injector must spend at the injection temperature. The resin being used for this project is limited to 24 hours at 80ºC.

4.4.4 Increase fibre volume fraction

The prototype part and mould were designed for a volume fraction of 50%. Once mould machining had begun, it was learned that BHTC specifications call for a higher value of 57%. As the witness coupon plate cavity had not yet been machined, this was done with the preferred value of 57%. No filling problems were observed with the plate, so it was clear that the part could have had a higher fibre volume fraction.

For prototype 005, a fifth ply was added to the airfoil which increased the volume fraction from 50% to 62%. In addition, the material in the ply dropoffs was lengthened in an effort to further increase the fibre volume fraction at these locations and "pinch" the ends of the fabric. Also, the amount of unidirectional filler material was increased considerably to ensure a consistently high fibre volume fraction in these ply dropoff regions.

It was hoped that there would be several benefits from increasing the fibre volume fraction. First, increasing fibre volume fraction should increase the constraint on the fibres and reduce fibre washout problems. Second, reducing the amount of resin in the part should reduce the surface imperfections caused by resin shrinkage. Finally, increasing the fibre volume fraction improves the performance of the part by increasing its strength-to-weight ratio since it is the fibres that impart strength to the composite. However, it should be noted that increasing the fibre volume fraction decreases the permeability in the preform. If the permeability becomes too low, mould filling problems can occur resulting in dry spots in the part.

The results for this prototype (005) were excellent. The surface finish was the best of any part at that point, fibre washout was eliminated, and there did not appear to be any filling or other manufacturing problems as a result of this increase in fibre volume fraction. Therefore, a fifth ply was similarly added to all subsequent prototypes produced (006 to 008). It is recommended that the full size slat be designed from the start with a volume fraction on the order of 60%

4.4.5 Create exact fabric patterns

For prototypes 001 to 004, preforming was carried out with rectangles of fabric which were placed onto the inserts and then trimmed by hand to the correct size. This process was labour intensive, time consuming, and inconsistent. As a result, some time was spent before prototype 005 to develop exact patterns that could be cut on an automatic cutting table and placed onto the inserts without any manual trimming required (Figure 4.11). This change reduced the preforming time by more than half. It also made the process much more consistent because each ply in the pattern could only fit onto the insert with a certain orientation and fabric deformation.

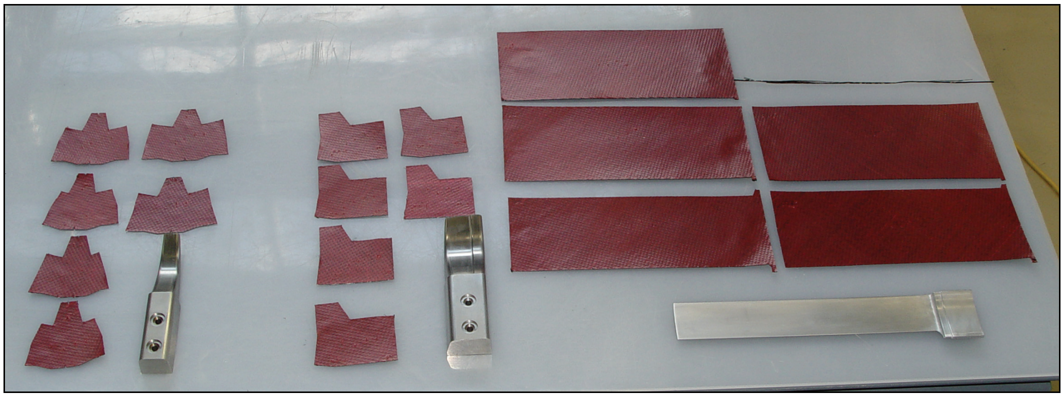

Figure 4.11: Exact fabric patterns for preform

4.4.6 Keep mould at cure temperature

The specifications for the resin being used for this project (CYCOM® 890 RTM) indicate that it is possible to carry out injections with the mould already heated to the cure temperature of 180ºC. This was attempted beginning with prototype 005 and offered a number of advantages. The production cycle time can be greatly reduced by avoiding the temperature ramp up from 100 to 180ºC. Uneven heating of the mould during this ramp, which can cause resin shrinkage on one side of the part, is also avoided. Demoulding the part at an elevated temperature further reduces the production cycle time and avoids any potential damage to the part during cooling due to the greater coefficient of thermal expansion of the mould. In a production environment, it might be possible to simply leave the mould at 180ºC to produce multiple parts without the need for any heat-up and cool-down time. Inserts being used for preforming, however, are required to be at room temperature since the tackiness of the fabric is lost at too high a temperature.

4.4.7 Improve injection hardware

The design and selection of hardware to transfer resin into and out of the mould is challenging. This hardware consists of a combination of tubes and fittings which must be able to withstand high temperature and pressure while maintaining an air-tight seal. Ideally, the injection and venting hardware should be simple to disconnect once mould filling is complete. After cure, any remaining hardware generally contains a mixture of cured and uncured resin. This hardware must be cleaned or scrapped after each injection. The ideal system would be simple to clean and require a minimum amount of scrap, disassembly, and re-installation.

After improving the preforming process with better patterns, hardware installation and cleaning was found to be the next most time consuming aspect of the manufacturing process. For this reason, as well as the discovery of a leak at the mould inlet during prototype 007, a new hardware setup was devised for prototype 008 (Figure 4.12). The new system provided a more secure connection to the mould and included a vertical column of resin which would prevent air bubbles from entering the mould when replacing the pressure pot with a compressed air line. It also replaced the metal tubing close to the mould, where resin in the lines tends to solidify, with Teflon® tubing. Any solidified resin would then be easier to remove from the tubing, ideally with compressed air. If cured resin could not be removed, the Teflon® tubing would be more economical to replace than aluminum tubing.

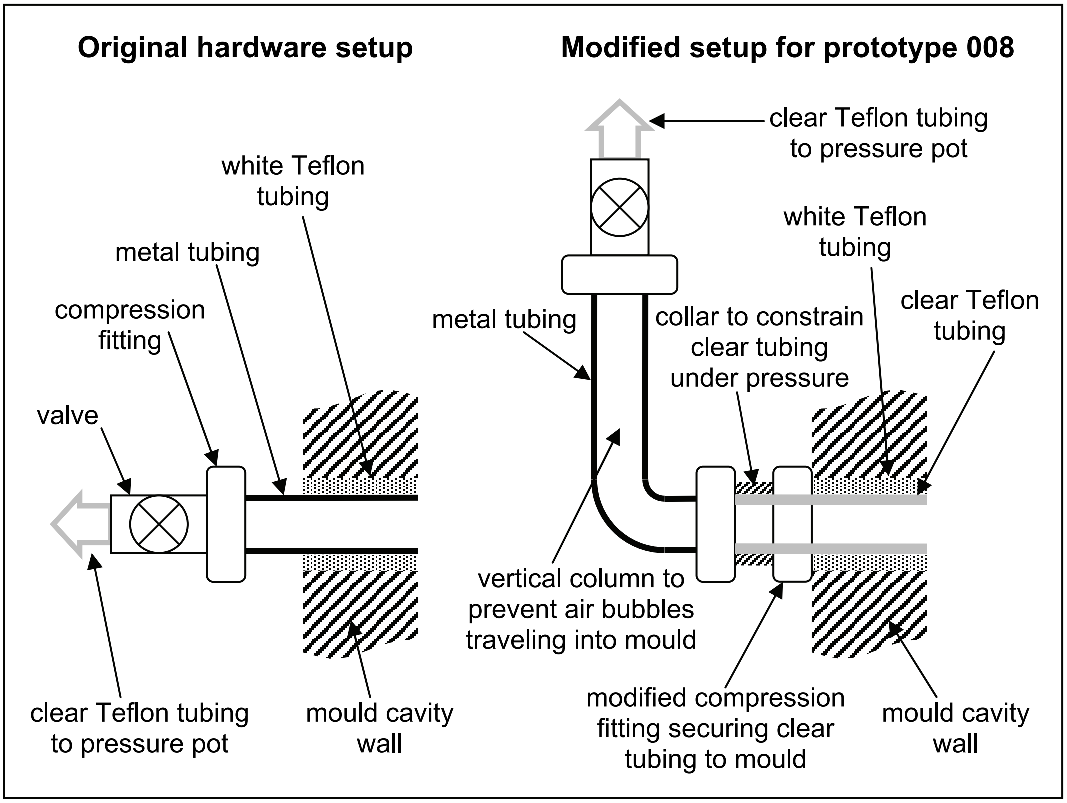

Figure 4.12: Injection hardware schematics

In practice, the new system performed well for prototype 008 with no leaks even under pressures exceeding 690 kPa (100 psi). However, it was observed that some air bubbles appeared to be entering the mould once the pressure pot was replaced with compressed air, though it is unclear where they originated. After demoulding, the cured plugs of resin in the injection lines could not be removed with compressed air. The hardware had to be disassembled and some of the clear Teflon® tubing scrapped. Clearly there is more work to be done to improve the injection system, but the steps taken so far already represent an improvement.

4.5 Further recommendations

Despite the improvements made to the process to date, many potential improvements remain:

1. Use fabric with a smaller tow size, 3K rather than 6K for example. The current fabric is quite coarse compared to the small geometry of the part being produced. A single tow out of place or missing represents a significant amount of material for this part. Although there were no serious preforming difficulties with the 6K fabric, fabric with a smaller tow size might have better drapability for the small and complex geometry of the slat.
2. Increase the fibre volume fraction of the part from 50% to 60%. As mentioned above, this increase was demonstrated to be feasible and offers a number of advantages. This increase should be designed into the mould from the start so the entire part has a consistent fibre volume fraction.
3. Add scribe lines to the mould inserts. These would be useful for positioning fabric onto the inserts during preforming. Also, marks could transfer to the part during cure and be used for trimming the part and positioning the fastener holes to be drilled in the brackets.
4. Design mould inserts to naturally protect any critical surfaces. Currently, if either of the two bracket inserts or the upper insert are placed face down on a table, they rest on a surface which defines the part. Repeatedly placing them in this way scuffs and scratches this critical surface. Avoiding this damage was found to be difficult even in a relatively controlled laboratory production environment. These inserts should have been designed to ensure that no matter how they are stored, they are not resting on a critical surface.
5. Include fasteners in the mould design to attach the lower insert to the modular mould cavity base plate. This would fix the relative positions of these two components making it easier to install the pressure and

temperature sensors through them. It would also allow this assembly to be flipped upside down further simplifying installation of the sensors. Currently, the sensors can only be accessed from under the mould.

6. Use a smaller witness coupon plate size. The size should be minimized based on production requirements for the type, size, and number of testing coupons required per part. Currently, the witness coupon uses more material than the prototype slat itself and may be larger than necessary.
7. Add insulation to the mould. Currently, sheets of 25 mm (1") thick insulating panels cover most of the upper and lower surfaces of the mould, leaving the remaining surfaces of the mould exposed to ambient air. Insulating the entire mould would improve energy efficiency and reduce the operator hazard of burning. However, this should be done without hindering mould assembly and disassembly.
8. Improve the injection hardware used to transfer resin into and out of the mould. As mentioned above, some progress was made on this topic but further improvements are still possible. The particular solution selected would depend on the production environment and required production cycle.
9. Use a steel mandrel. The aluminum mandrel scratches easily when it is removed from the cured part and must be re-polished and surface treated between each injection. In production this would not only slow down the process but also require periodic replacement of the mandrel due to the loss of material during each re-polishing. Aluminum was initially selected for the mandrel because it has a greater coefficient of thermal expansion than steel. It was hoped that after curing the part at 180ºC and then cooling back to room temperature, the mandrel would shrink inside the airfoil as it cooled making it easier to remove. However, results of the manufacturing trials showed that the thermal contraction of the aluminum mandrel was not enough to allow simple extraction, even after cooling the part and mandrel in a freezer. It is therefore recommended that a steel mandrel be tested in future trials. Although its lower coefficient of

thermal expansion will in theory make the extraction force increase, it is possible that this would be offset by the steel's much greater surface hardness with the end result being less surface damage.

10. Use a jig to trim the part with a diamond saw and round off any remaining sharp edges by hand using a small rotary sander. This would make the post-machining faster and more consistent than performing all trimming by hand as was done with prototype 001. A drill fixture could also be used to position and orient the fastener holes in the brackets.

4.6 Summary

Eight prototype slats were produced by RTM. All parts but one were well filled (the one poorly filled part was the result of insufficient resin in the injector) and had generally good surface finishes. Mechanical testing will be performed to determine part quality in terms of mechanical properties. In terms of visual characteristics such as surface finish and fibre washout, part quality generally improved over the course of production. A number of important lessons were learned and these can be applied to the design and production of full-size slats as well as other parts produced by RTM in the future.

Chapter 5 Conclusions

As part of "CRIAQ project 1.15: Optimized Design of Composite Parts", a composite aeronautical component is being designed and produced by resin transfer moulding (RTM). The component is a Bell 407 leading edge slat with four attachment brackets which are being consolidated into a single composite part. The goal is to demonstrate that a composite component can provide improved performance over existing metallic components while still being cost-effective. RTM is well suited to this task as it can produce parts with good properties and complex shapes without the expense of an autoclave.

To date, work on the project has focused on designing and producing a half-length prototype. A set of inserts were designed to produce prototype slats using an existing RTM modular mould cavity. The modular concept provided a cost effective way of obtaining a self-contained mould that is suitable for a production environment. The mould inserts were designed taking into consideration results from flow modelling and stress analysis as well as practical manufacturing concerns such as preforming and demoulding. The final mould design consisted of a mandrel for the hollow airfoil, one bracket insert for each of the two brackets, and an upper and lower insert for the outer surface of the part. A flat plate was also included in the mould to be used as a witness coupon for quality control testing.

All composite manufacturing was carried out at AMTC. A total of eight prototype slats had been produced at the time of writing. Injections were carried out using a pressure pot system with vacuum assistance. A number of changes and improvements were made to the manufacturing procedure over the course of producing the eight prototypes. Most parts were well filled and had a good surface finish. Turnaround times of 1 day per part were obtained twice. In a production environment and with additional sets of inserts the production rate could be increased considerably.

The prototypes produced will be subjected to mechanical testing to validate the manufacturing process and stress analysis. The results of these tests as well as the experience gained and lessons learned from prototype design and manufacturing will be used to design and produce full-size versions of the composite leading edge slat. Though many improvements are still possible for the design and production of a composite aeronautical component by RTM, the success of the project to date is an indication that RTM is a viable manufacturing method for industry.

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Appendix A: Injection data

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AMTC COMPOSITE GROUP

INJECTION LOG SHEET

Project	CRIAQ 1.15 RTM Slat	**Project code**	46M4-J003
Part(s)	Prototype slat Witness coupon plate	**Part number(s)**	46M4-J003-01-001 46M4-J003-02-001

MATERIALS

Name	Manufacturer	Lot-roll #	Mfg Date
CYCOM 890-1 pregreg (RIGIDITE 890-1 WG30-500 6K 5HS) part # 21418050	Cytec	8021717-001	02 Oct 2004
CYCOM 890 RTM resin part # 21407787	Cytec	7753451-0006	29 Jul 2004

Comments

PREFORM

Component	Material	Layup
Airfoil	6K-5HS	$[45]_4$
Brackets	6K-5HS	$[0 / 45_2]_s$
2 noodles for full bracket	tows from 6K-5HS	unknown number of tows
Witness coupon plate	6K-5HS	[0/45/0/45/0/45/0]

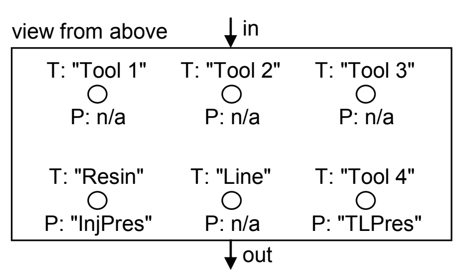
Operator(s)	M.-A. Octeau, J. O'Flynn, L. Khoun	**Date**	20 Mar 2007

Comments 0 indicates a (0/90) ply, 45 indicates a +-45 ply. Note that for 5HS to be symmetric, orientation of upper and lower half of laminate must be offset by 90º. Witness plate is therefore not quite symmetric because of odd layer of (0/90) in the middle.

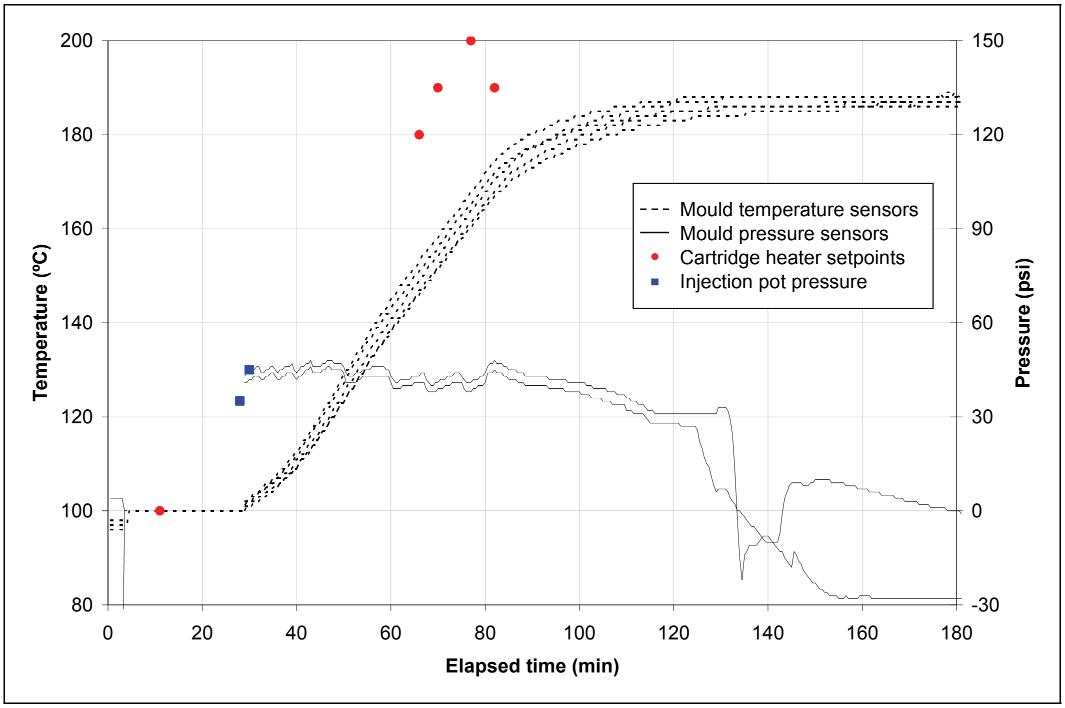
INJECTION

Operator(s)	M.-A. Octeau, J. O'Flynn, L. Khoun	**Date**	20 Mar 2007
Mould	Small modular mould	**Resin preheat**	80ºC
Injector	Pressure pot	**Mould preheat**	100ºC
Data acquisition	Radius injector	**Vacuum level**	none
		Vacuum leak rate	unknown

Sensor layout



Comments Cure monitoring with the dielectric sensor was not operational. Injector log file times are behind by 38 minutes.



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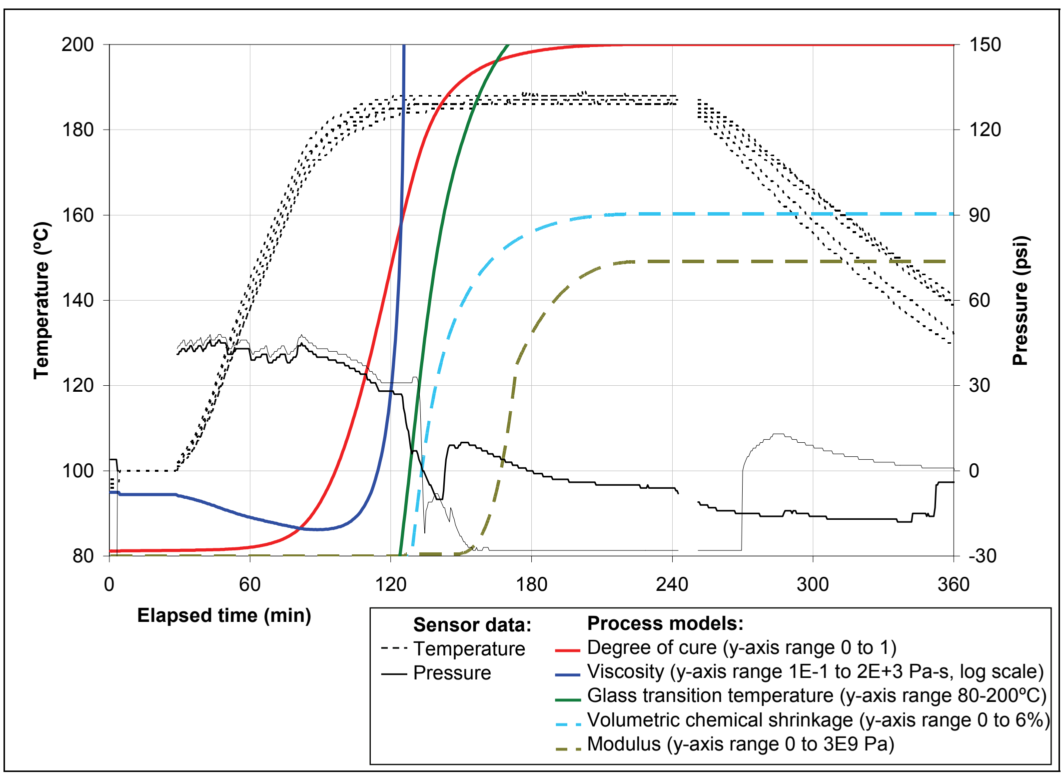
Temperature (ºC)
Pressure (psi)
Elapsed time (min)
Mould temperature sensors
Mould pressure sensors
Cartridge heater setpoints
Injection pot pressure



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360
Temperature (ºC)
Pressure (psi)
Elapsed time (min)
Sensor data:
Temperature
Pressure
Process models:
Degree of cure (y-axis range 0 to 1)
Viscosity (y-axis range 1E-1 to 2E+3 Pa-s, log scale)
Glass transition temperature (y-axis range 80-200ºC)
Volumetric chemical shrinkage (y-axis range 0 to 6%)
Modulus (y-axis range 0 to 3E9 Pa)

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INJECTION LOG SHEET

AMTC COMPOSITE GROUP

Project	CRIAQ 1.15 RTM Slat	**Project code**	46M4-J003
Part(s)	Prototype slat	**Part number(s)**	46M4-J003-01-002
	Witness coupon plate		46M4-J003-02-002

MATERIALS

Name	Manufacturer	Lot-roll #	Mfg Date
CYCOM 890-1 pregreg (RIGIDITE 890-1 WG30-500 6K 5HS) part # 21418050	Cytec	8021717-001	02 Oct 2004
CYCOM 890 RTM resin part # 21407787	Cytec	7753451-0006	29 Jul 2004

Comments

PREFORM

Component	Material	Layup
Airfoil	6K-5HS	$[45]_4$
Brackets	6K-5HS	$[45 / 0 / 45]_s$
2 noodles for full bracket, 1 for airfoil TE	tows from 6K-5HS	3 tows
Witness coupon plate	6K-5HS	[0/45/0/45/0/45/0/45/0]

Operator(s) M.-A. Octeau, J. O'Flynn, L. Khoun **Date** 26 Apr 2007

Comments 0 indicates a (0/90) ply, 45 indicates a +-45 ply. Note that for 5HS to be symmetric, orientation of upper and lower half of laminate must be offset by 90º. Witness plate is therefore not quite symmetric because of odd layer of (0/90) in the middle.
Trailing edge of airfoil had measured ply dropoff starting this time.

INJECTION

Operator(s)	M.-A. Octeau, J. O'Flynn, L. Khoun	**Date**	26 Apr 2007
Mould	Small modular mould	**Resin preheat**	80ºC
Injector	Pressure pot	**Mould preheat**	100ºC
Data acquisition	Radius injector, dielectric sensor computer	**Vacuum level**	-25 in Hg
		Vacuum leak rate	unknown

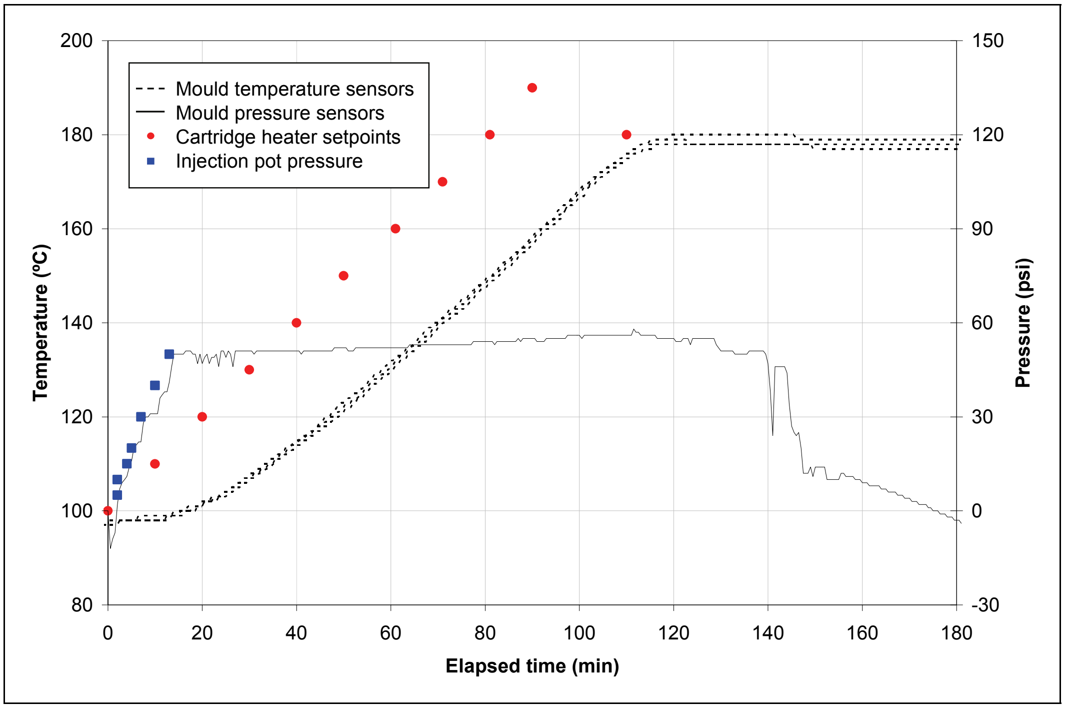
Sensor layout

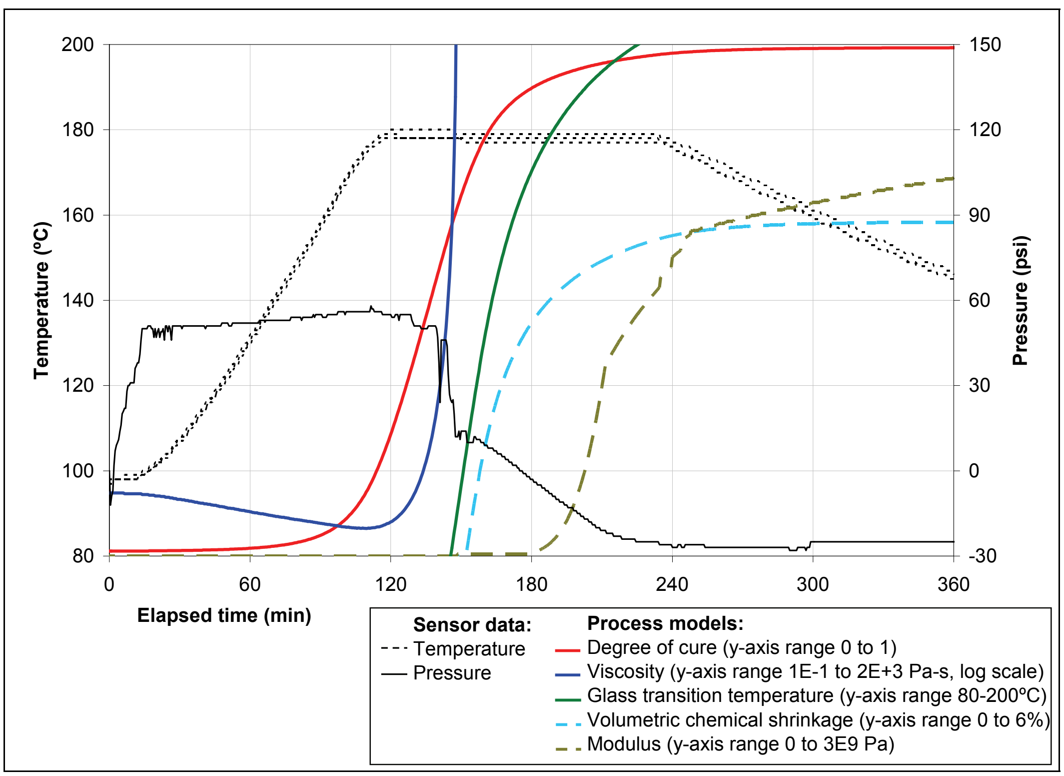
view from above ↓ in

T: "Tool 1" ○ P: n/a	T: "Resin" ○ P: "InjPres"	T: "Tool 2" ○ P: n/a
T: "Tool 3" ○ P: n/a	T: "Line" ○ P: "TLPres"	T: "Tool 4" ○ P: n/a

↓ out

Comments Dielectric computer ~6 min ahead of injector computer.


Mould temperature sensors
Mould pressure sensors
Cartridge heater setpoints
Injection pot pressure
Temperature (ºC)
Pressure (psi)
Elapsed time (min)


Temperature (ºC)
Pressure (psi)
Elapsed time (min)
Sensor data:
Temperature
Pressure
Process models:
Degree of cure (y-axis range 0 to 1)
Viscosity (y-axis range 1E-1 to 2E+3 Pa-s, log scale)
Glass transition temperature (y-axis range 80-200ºC)
Volumetric chemical shrinkage (y-axis range 0 to 6%)
Modulus (y-axis range 0 to 3E9 Pa)

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INJECTION LOG SHEET

AMTC COMPOSITE GROUP

Project	CRIAQ 1.15 RTM Slat	**Project code**	46M4-J003
Part(s)	Prototype slat	**Part number(s)**	46M4-J003-01-003
	Witness coupon plate		46M4-J003-02-003

MATERIALS

Name	Manufacturer	Lot-roll #	Mfg Date
CYCOM 890-1 pregreg (RIGIDITE 890-1 WG30-500 6K 5HS) part # 21418050	Cytec	8021717-001	02 Oct 2004
CYCOM 890 RTM resin part # 21407787	Cytec	7753451-0006	29 Jul 2004

Comments

PREFORM

Component	Material	Layup
Airfoil	6K-5HS	$[45]_4$
Brackets	6K-5HS	$[45 / 0 / 45]_s$
2 noodles for full bracket, 0 for airfoil TE	tows from 6K-5HS	3 tows
Witness coupon plate	6K-5HS	[0/45/0/45/0/45/0/45/0]

Operator(s) M.-A.Octeau, J.O'Flynn, L.Khoun, S.Roy **Date** 23 May 2007

Comments 0 indicates a (0/90) ply, 45 indicates a +-45 ply. Note that for 5HS to be symmetric, orientation of upper and lower half of laminate must be offset by 90º. Witness plate is therefore not quite symmetric because of odd layer of (0/90) in the middle.
Trailing edge of airfoil had measured ply dropoff.

INJECTION

Operator(s)	M.-A.Octeau, J.O'Flynn, L.Khoun, S.Roy	**Date**	23 May 2007
Mould	Small modular mould	**Resin preheat**	80ºC
Injector	Pressure pot	**Mould preheat**	100ºC
Data acquisition	Radius injector, no dielectric sensor computer	**Vacuum level**	-25 in Hg
		Vacuum leak rate	1.2 torr / min

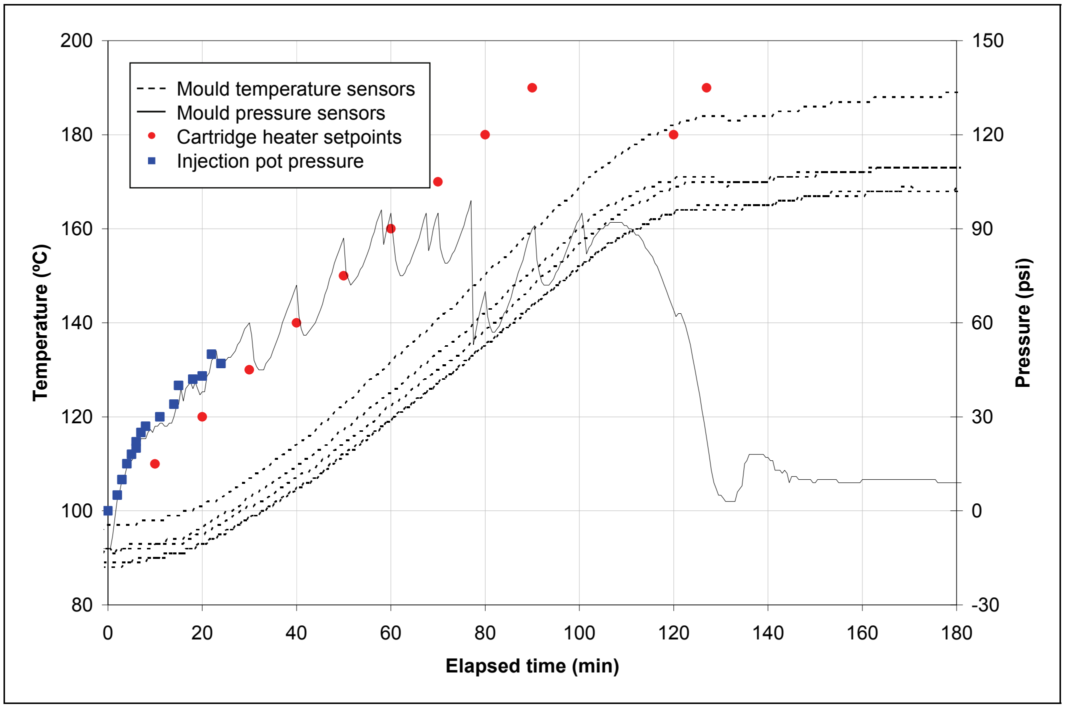
Sensor layout

view from above ↓ in

T: "Tool 4" ○ P: n/a	T: "Resin" ○ P: "InjPres"	T: "Tool 3" ○ P: n/a
T: defect ○ P: n/a	T: "Tool 1" ○ P: n/a	T: "Tool 2" ○ P: n/a

↓ out

Comments


Mould temperature sensors
Mould pressure sensors
Cartridge heater setpoints
Injection pot pressure
Temperature (ºC)
Pressure (psi)
Elapsed time (min)
200
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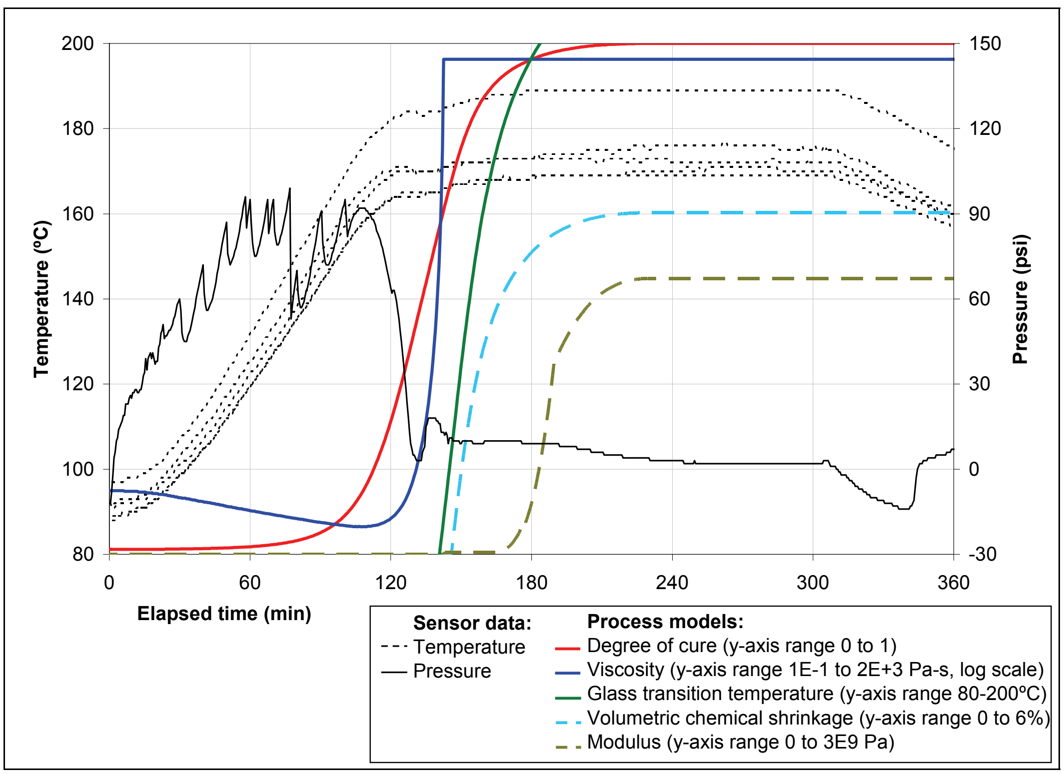
Temperature (ºC)
Pressure (psi)
Elapsed time (min)
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Sensor data:
Temperature
Pressure
Process models:
Degree of cure (y-axis range 0 to 1)
Viscosity (y-axis range 1E-1 to 2E+3 Pa-s, log scale)
Glass transition temperature (y-axis range 80-200ºC)
Volumetric chemical shrinkage (y-axis range 0 to 6%)
Modulus (y-axis range 0 to 3E9 Pa)

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INJECTION LOG SHEET

AMTC
COMPOSITE GROUP

Project	CRIAQ 1.15 RTM Slat	**Project code**	46M4-J003
Part(s)	Prototype slat Witness coupon plate	**Part number(s)**	46M4-J003-01-004 46M4-J003-02-004

MATERIALS

Name	Manufacturer	Lot-roll #	Mfg Date
CYCOM 890-1 pregreg (RIGIDITE 890-1 WG30-500 6K 5HS) part # 21418050	Cytec	8021717-001	02 Oct 2004
CYCOM 890 RTM resin part # 21407787	Cytec	7753451-0006	29 Jul 2004

Comments

PREFORM

Component	Material	Layup
Airfoil	6K-5HS	$[45]_4$
Brackets	6K-5HS	$[45 / 0 / 45]_s$
2 noodles for full bracket, 1 for airfoil TE	tows from 6K-5HS	3 tows
Witness coupon plate	6K-5HS	[0/45/0/45/0/45/0/45/0]

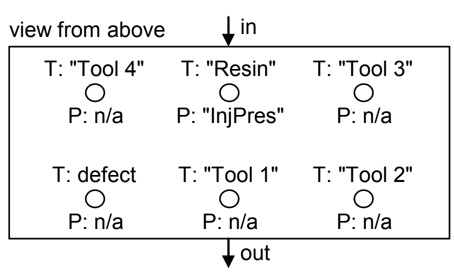
Operator(s)	M.-A.Octeau, J.O'Flynn, S.Roy	**Date**	24 May 2007

Comments 0 indicates a (0/90) ply, 45 indicates a +-45 ply. Note that for 5HS to be symmetric, orientation of upper and lower half of laminate must be offset by 90º. Witness plate is therefore not quite symmetric because of odd layer of (0/90) in the middle.
Trailing edge of airfoil had measured ply dropoff.

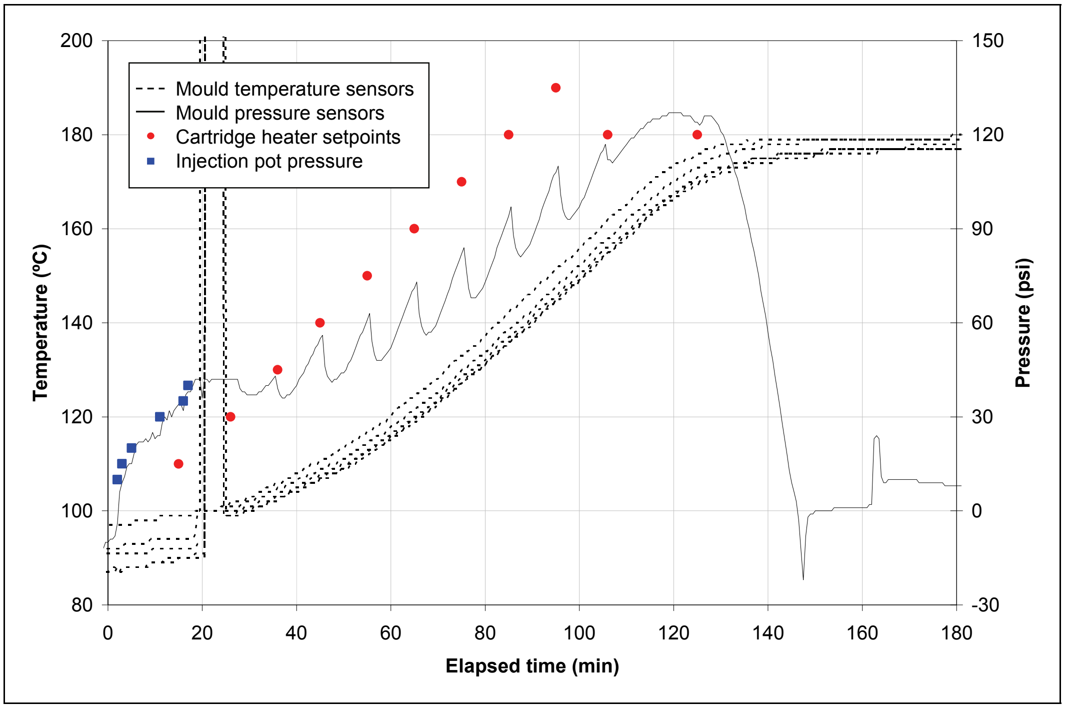
INJECTION

Operator(s)	M.-A.Octeau, J.O'Flynn, S.Roy	**Date**	24 May 2007
Mould	Small modular mould	**Resin preheat**	80ºC
Injector	Pressure pot	**Mould preheat**	100ºC
Data acquisition	Radius injector, no dielectric sensor computer	**Vacuum level**	-25 in Hg
		Vacuum leak rate	1.96 torr / min

Sensor layout



Comments


Mould temperature sensors
Mould pressure sensors
Cartridge heater setpoints
Injection pot pressure
Temperature (ºC)
Pressure (psi)
Elapsed time (min)
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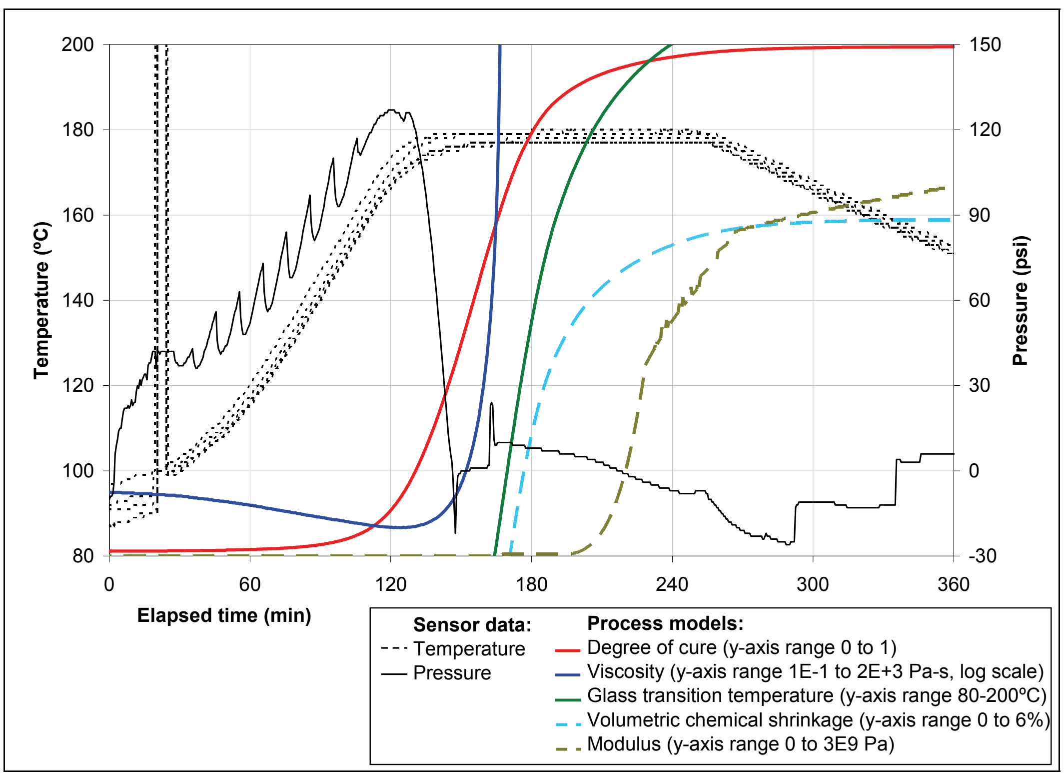
Temperature (ºC)
Pressure (psi)
Elapsed time (min)
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Sensor data:
Temperature
Pressure
Process models:
Degree of cure (y-axis range 0 to 1)
Viscosity (y-axis range 1E-1 to 2E+3 Pa-s, log scale)
Glass transition temperature (y-axis range 80-200ºC)
Volumetric chemical shrinkage (y-axis range 0 to 6%)
Modulus (y-axis range 0 to 3E9 Pa)

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INJECTION LOG SHEET

COMPOSITE GROUP

Project	CRIAQ 1.15 RTM Slat	**Project code**	46M4-J003
Part(s)	Prototype slat	**Part number(s)**	46M4-J003-01-005
	Witness coupon plate		46M4-J003-02-005

MATERIALS

Name	Manufacturer	Lot-roll #	Mfg Date
CYCOM 890-1 pregreg (RIGIDITE 890-1 WG30-500 6K 5HS) part # 21418050	Cytec	8021717-001	02 Oct 2004
CYCOM 890 RTM resin part # 21407787	Cytec	7753451-0006	29 Jul 2004

Comments

PREFORM

Component	Material	Layup
Airfoil	6K-5HS	$[45]_5$
Brackets	6K-5HS	$[45 / 0 / 45]_s$
2 noodles for full bracket, 1 for airfoil TE	tows from 6K-5HS	6 tows for airfoil, 18 for bracket
Witness coupon plate	6K-5HS	[0/45/0/45/0/45/0/45/0]

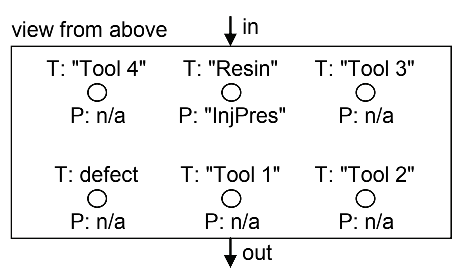
Operator(s)	J.O'Flynn, S.Roy, S. Phillips	**Date**	20 Jun 2007

Comments 0 indicates a (0/90) ply, 45 indicates a +-45 ply. Note that for 5HS to be symmetric, orientation of upper and lower half of laminate must be offset by 90º. Witness plate and now airfoil are therefore not quite symmetric because of odd layer in the middle. First time using exact patterns pre-cut on Eastman cutting table.

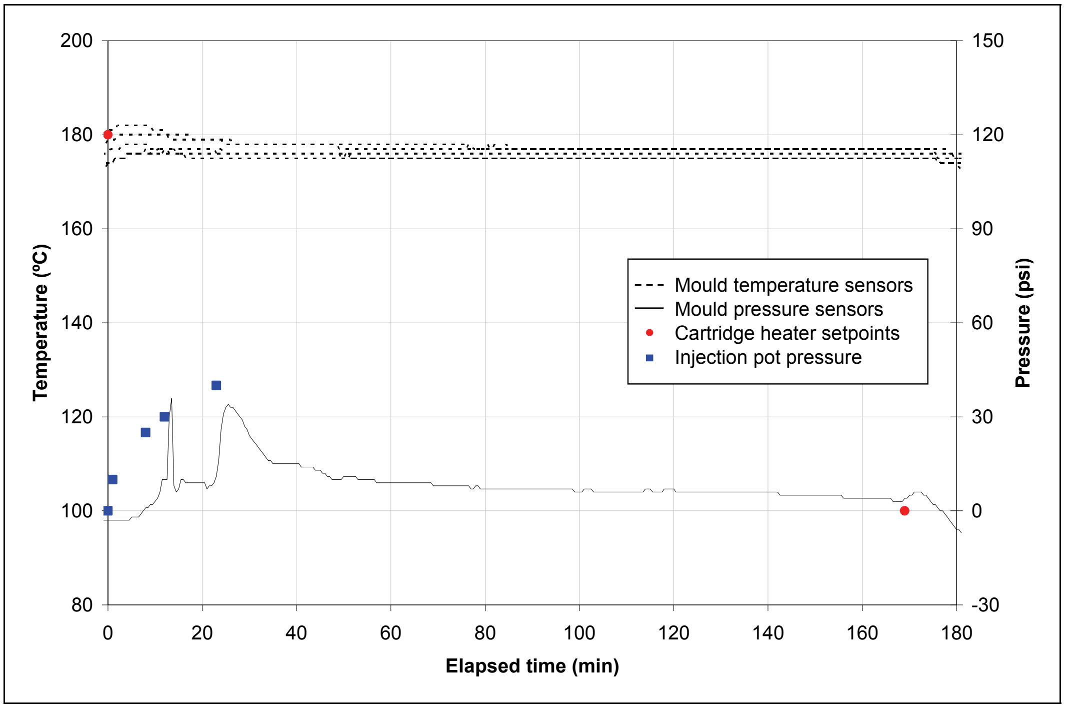
INJECTION

Operator(s)	M.-A.Octeau, J.O'Flynn, S.Roy, S. Phillips	**Date**	20 Jun 2007
Mould	Small modular mould	**Resin preheat**	< 80ºC
Injector	Pressure pot	**Mould preheat**	~180ºC
Data acquisition	Radius injector, no dielectric sensor computer	**Vacuum level**	-25 in Hg
		Vacuum leak rate	1.38 torr / min

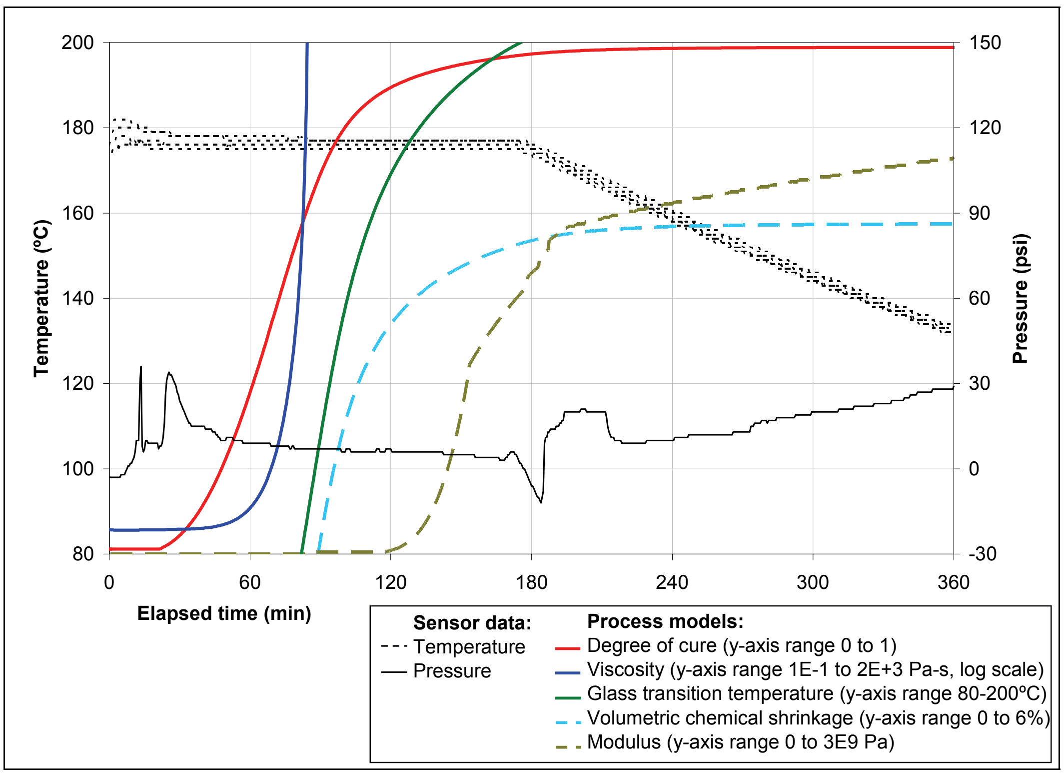
Sensor layout



Comments Vacuum pump didn't seem to be working well. Dried resin was covering the pressure sensor. Resin sat in pressure pot for some time while mould temperature was increased, resulting in a lower resin temperature in the can. Before injection, the resin appeared to be starting to gel after so much use. Slat outlet tube melted shut and was replaced during the injection.



Temperature (ºC)
Pressure (psi)
Elapsed time (min)
Mould temperature sensors
Mould pressure sensors
Cartridge heater setpoints
Injection pot pressure



Temperature (ºC)
Pressure (psi)
Elapsed time (min)
Sensor data:
Temperature
Pressure
Process models:
Degree of cure (y-axis range 0 to 1)
Viscosity (y-axis range 1E-1 to 2E+3 Pa-s, log scale)
Glass transition temperature (y-axis range 80-200ºC)
Volumetric chemical shrinkage (y-axis range 0 to 6%)
Modulus (y-axis range 0 to 3E9 Pa)

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COMPOSITE GROUP

INJECTION LOG SHEET

Project	CRIAQ 1.15 RTM Slat	**Project code**	46M4-J003
Part(s)	Prototype slat Witness coupon plate	**Part number(s)**	46M4-J003-01-006 46M4-J003-02-006

MATERIALS

Name	Manufacturer	Lot-roll #	Mfg Date
CYCOM 890-1 pregreg (RIGIDITE 890-1 WG30-500 6K 5HS) part # 21418050	Cytec	8021717-001	02 Oct 2004
CYCOM 890 RTM resin part # 21407787	Cytec	7756508-008	19 Dec 2005

Comments

PREFORM

Component	Material	Layup
Airfoil	6K-5HS	$[45]_5$
Brackets	6K-5HS	$[45 / 0 / 45]_s$
2 noodles for full bracket, 1 for airfoil TE	tows from 6K-5HS	6 tows for airfoil, 18 for bracket
Witness coupon plate	6K-5HS	[0/45/0/45/0/45/0/45/0]

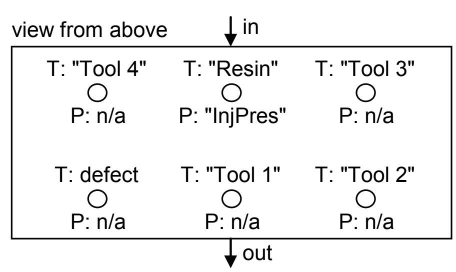
Operator(s) J.O'Flynn, S.Roy, S. Phillips **Date** 30 Jul 2007

Comments 0 indicates a (0/90) ply, 45 indicates a +-45 ply. Note that for 5HS to be symmetric, orientation of upper and lower half of laminate must be offset by 90º. Witness plate and now airfoil are therefore not quite symmetric because of odd layer in the middle.

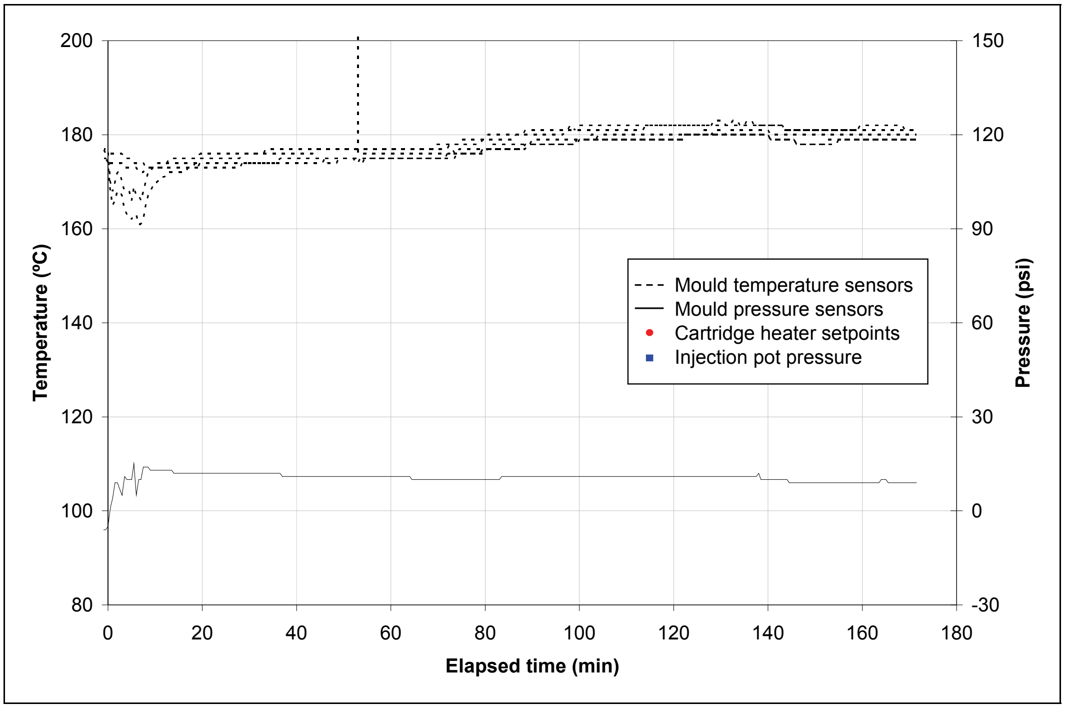
INJECTION

Operator(s)	M.-A.Octeau, J.O'Flynn, S.Roy, S. Phillips	**Date**	30 Jul 2007
Mould	Small modular mould	**Resin preheat**	80ºC
Injector	Pressure pot	**Mould preheat**	180ºC
Data acquisition	Radius injector, no dielectric sensor computer	**Vacuum level**	-25 in Hg
		Vacuum leak rate	1.53 torr / min

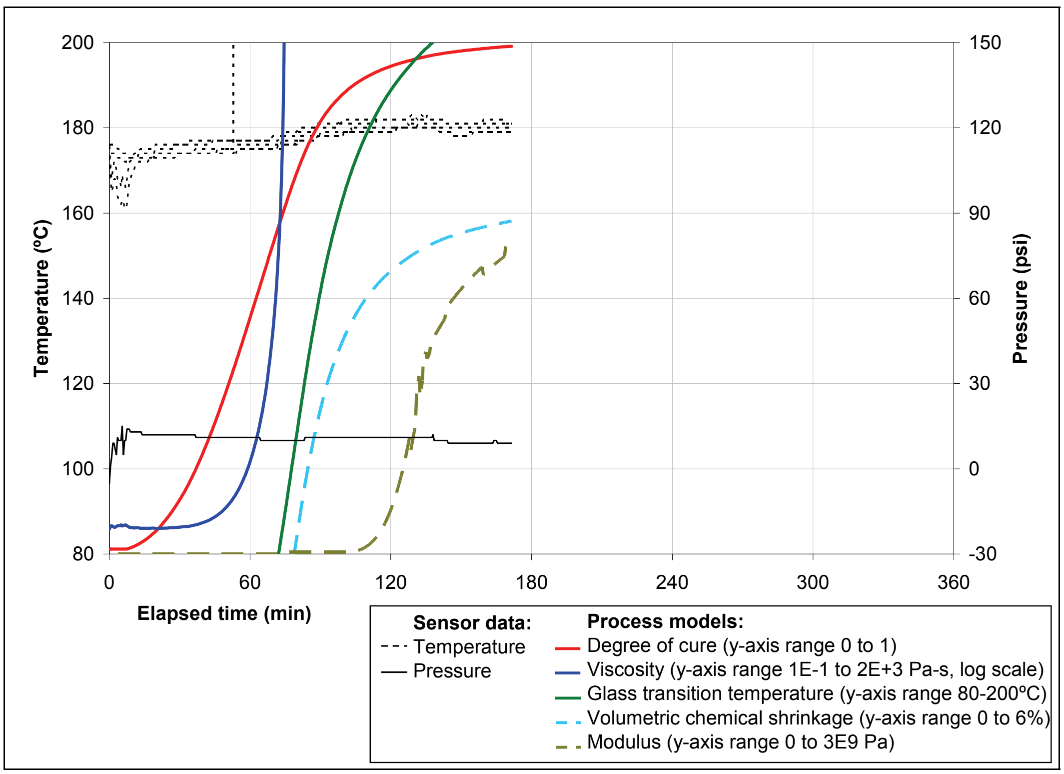
Sensor layout



Comments New resin much less viscous than old used for previous 5 prototypes. Ran out of resin in injection pot so air entered part. Began injection with full vacuum (-28 in Hg) then reduced to -25 as usual.



Mould temperature sensors
Mould pressure sensors
Cartridge heater setpoints
Injection pot pressure
Temperature (ºC)
Pressure (psi)
Elapsed time (min)



Temperature (ºC)
Pressure (psi)
Elapsed time (min)
Sensor data:
Temperature
Pressure
Process models:
Degree of cure (y-axis range 0 to 1)
Viscosity (y-axis range 1E-1 to 2E+3 Pa-s, log scale)
Glass transition temperature (y-axis range 80-200ºC)
Volumetric chemical shrinkage (y-axis range 0 to 6%)
Modulus (y-axis range 0 to 3E9 Pa)

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INJECTION LOG SHEET

COMPOSITE GROUP

Project	CRIAQ 1.15 RTM Slat	**Project code**	46M4-J003
Part(s)	Prototype slat Witness coupon plate	**Part number(s)**	46M4-J003-01-007 46M4-J003-02-007

MATERIALS

Name	Manufacturer	Lot-roll #	Mfg Date
CYCOM 890-1 pregreg (RIGIDITE 890-1 WG30-500 6K 5HS) part # 21418050	Cytec	8021717-001	02 Oct 2004
CYCOM 890 RTM resin part # 21407787	Cytec	7756508-008	19 Dec 2005

Comments

PREFORM

Component	Material	Layup
Airfoil	6K-5HS	$[45]_5$
Brackets	6K-5HS	$[45 / 0 / 45]_s$
2 noodles for full bracket, 1 for airfoil TE	tows from 6K-5HS	6 tows for airfoil, 18 for bracket
Witness coupon plate	6K-5HS	[0/45/0/45/0/45/0/45/0]

Operator(s)	J.O'Flynn, S.Roy	**Date**	31 Jul 2007

Comments 0 indicates a (0/90) ply, 45 indicates a +-45 ply. Note that for 5HS to be symmetric, orientation of upper and lower half of laminate must be offset by 90º. Witness plate and now airfoil are therefore not quite symmetric because of odd layer in the middle.

INJECTION

Operator(s)	M.-A.Octeau, J.O'Flynn, S.Roy	**Date**	31 Jul 2007
Mould	Small modular mould	**Resin preheat**	80ºC
Injector	Pressure pot	**Mould preheat**	180ºC
Data acquisition	Radius injector, no dielectric sensor computer	**Vacuum level**	-25 in Hg
		Vacuum leak rate	0.55 torr / min

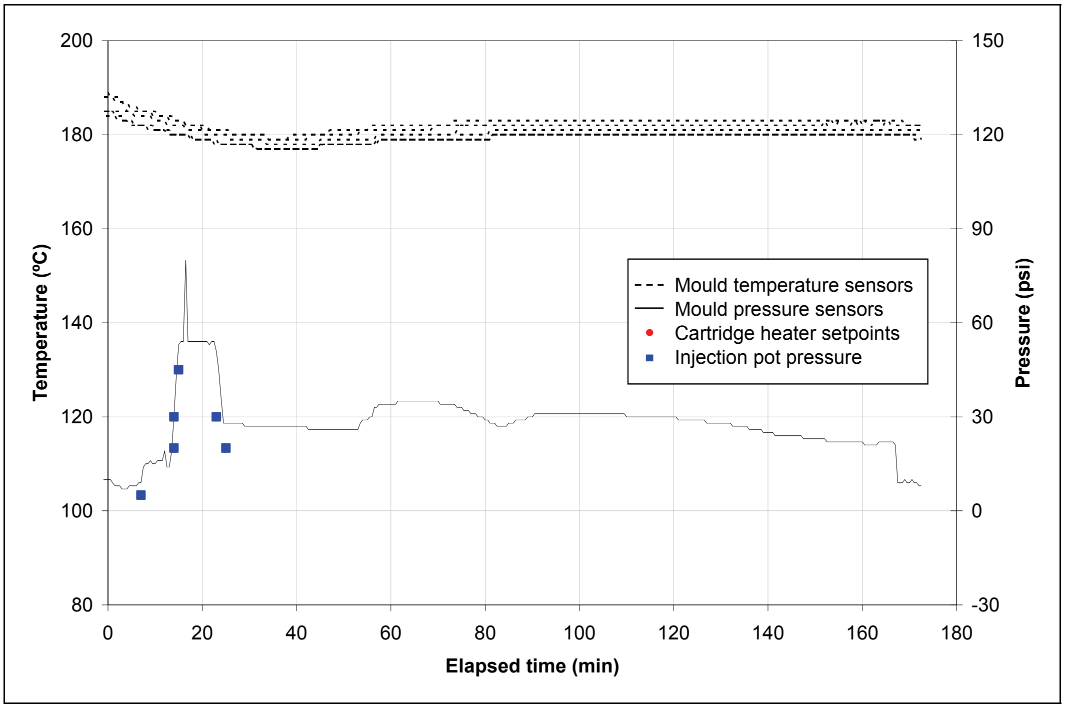
Sensor layout

view from above ↓ in

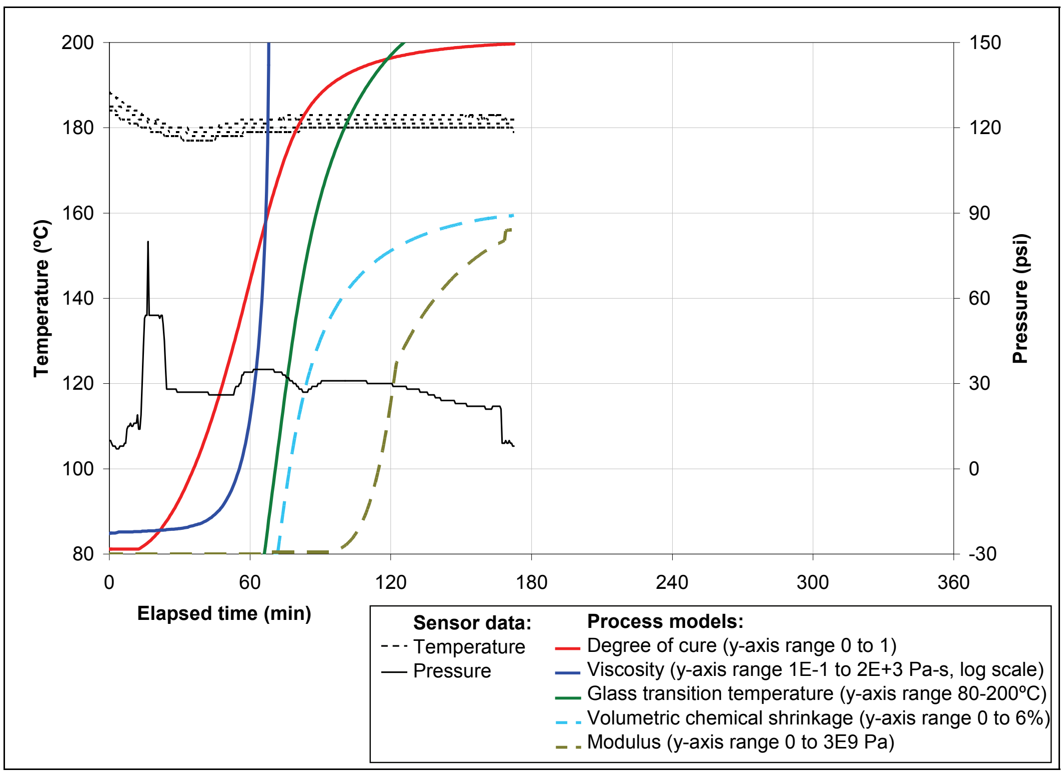
T: "Tool 4" ○ P: n/a	T: "Resin" ○ P: "InjPres"	T: "Tool 3" ○ P: n/a
T: defect ○ P: n/a	T: "Tool 1" ○ P: n/a	T: "Tool 2" ○ P: n/a

↓ out

Comments



Mould temperature sensors
Mould pressure sensors
Cartridge heater setpoints
Injection pot pressure
Temperature (ºC)
Pressure (psi)
Elapsed time (min)



Temperature (ºC)
Pressure (psi)
Elapsed time (min)
Sensor data:
Temperature
Pressure
Process models:
Degree of cure (y-axis range 0 to 1)
Viscosity (y-axis range 1E-1 to 2E+3 Pa-s, log scale)
Glass transition temperature (y-axis range 80-200ºC)
Volumetric chemical shrinkage (y-axis range 0 to 6%)
Modulus (y-axis range 0 to 3E9 Pa)

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INJECTION LOG SHEET

AMTC COMPOSITE GROUP

Project	CRIAQ 1.15 RTM Slat	**Project code**	46M4-J003
Part(s)	Prototype slat Witness coupon plate	**Part number(s)**	46M4-J003-01-008 46M4-J003-02-008

MATERIALS

Name	Manufacturer	Lot-roll #	Mfg Date
CYCOM 890-1 pregreg (RIGIDITE 890-1 WG30-500 6K 5HS) part # 21418050	Cytec	8021717-001	02 Oct 2004
CYCOM 890 RTM resin part # 21407787	Cytec	7756508-008	19 Dec 2005

Comments

PREFORM

Component	Material	Layup
Airfoil	6K-5HS	$[45]_5$
Brackets	6K-5HS	$[45 / 0 / 45]_s$
2 noodles for full bracket, 1 for airfoil TE	tows from 6K-5HS	6 tows for airfoil, 18 for bracket
Witness coupon plate	6K-5HS	[0/45/0/45/0/45/0/45/0]

Operator(s)	J.O'Flynn, S.Roy, S. Phillips	**Date**	02 Aug 2007

Comments 0 indicates a (0/90) ply, 45 indicates a +-45 ply. Note that for 5HS to be symmetric, orientation of upper and lower half of laminate must be offset by 90º. Witness plate and now airfoil are therefore not quite symmetric because of odd layer in the middle.

INJECTION

Operator(s)	M.-A.Octeau, J.O'Flynn, S.Roy, S. Phillips	**Date**	02 Aug 2007
Mould	Small modular mould	**Resin preheat**	80ºC
Injector	Pressure pot	**Mould preheat**	180ºC
Data acquisition	Radius injector, no dielectric sensor computer	**Vacuum level**	-25 in Hg
		Vacuum leak rate	1.09 torr / min

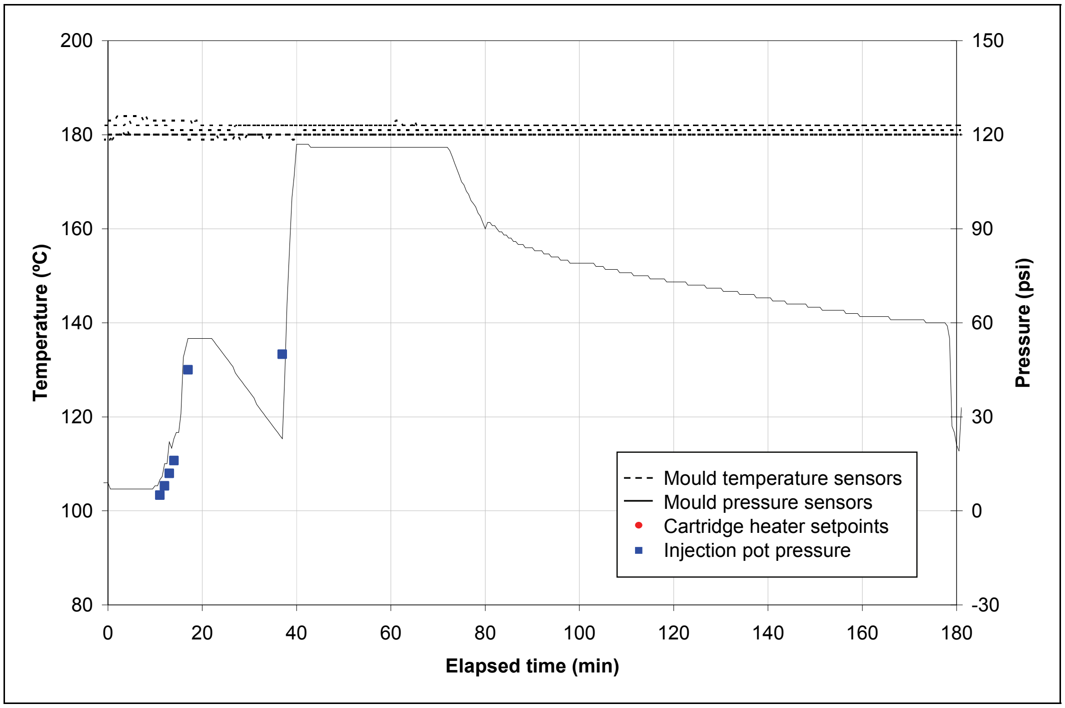
Sensor layout

view from above ↓ in

T: "Tool 4" ○ P: n/a	T: "Resin" ○ P: "InjPres"	T: "Tool 3" ○ P: n/a
T: defect ○ P: n/a	T: "Tool 1" ○ P: n/a	T: "Tool 2" ○ P: n/a

↓ out

Comments New hardware used allowing lab air pressure line to be connected to inlet after filling and removing pressure pot.



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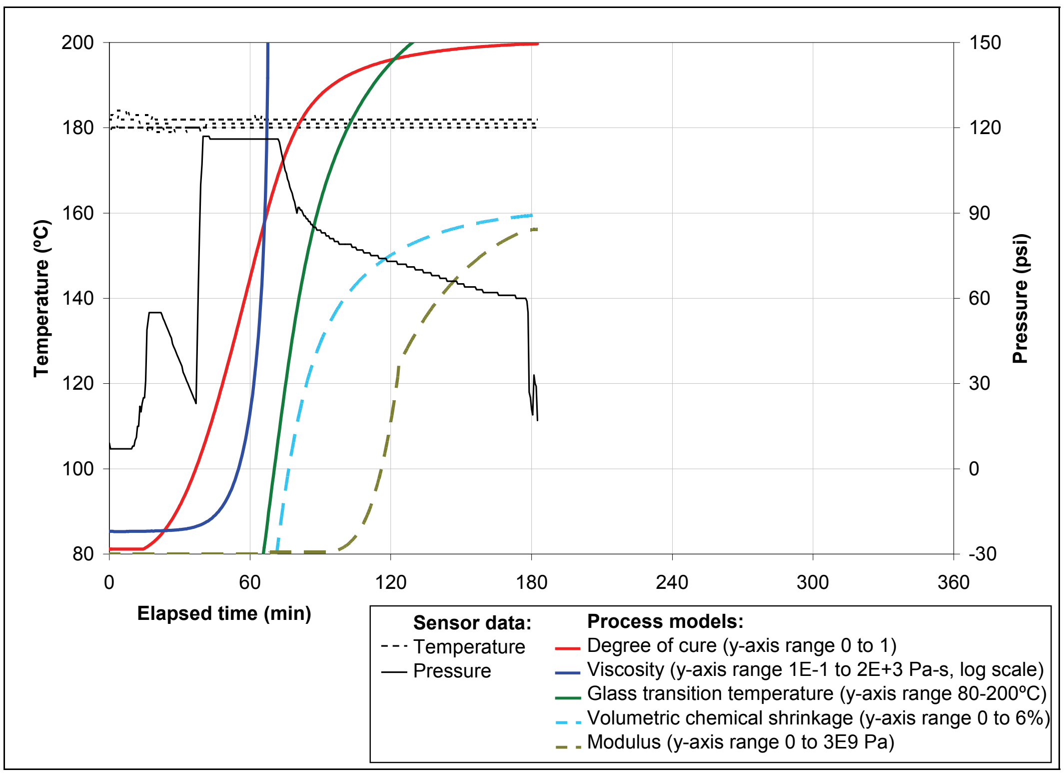
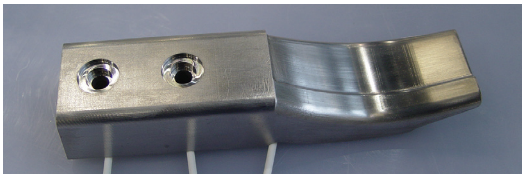
Temperature (ºC)
Pressure (psi)
Elapsed time (min)
Mould temperature sensors
Mould pressure sensors
Cartridge heater setpoints
Injection pot pressure



200
180
160
140
120
100
80
150
120
90
60
30
0
-30
0
60
120
180
240
300
360
Temperature (ºC)
Pressure (psi)
Elapsed time (min)
Sensor data:
Temperature
Pressure
Process models:
Degree of cure (y-axis range 0 to 1)
Viscosity (y-axis range 1E-1 to 2E+3 Pa-s, log scale)
Glass transition temperature (y-axis range 80-200ºC)
Volumetric chemical shrinkage (y-axis range 0 to 6%)
Modulus (y-axis range 0 to 3E9 Pa)

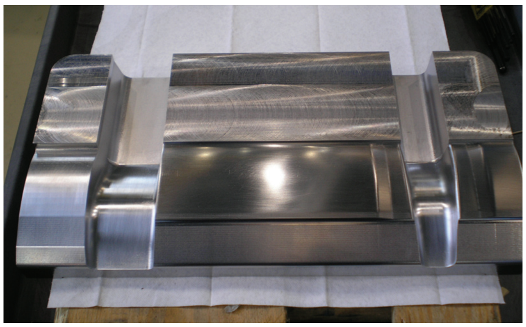
Appendix B: Manufacturing photographs

Mould components

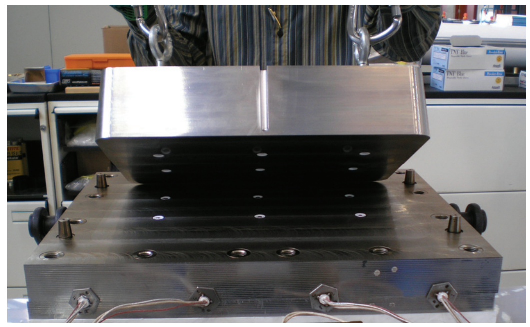


Half bracket insert

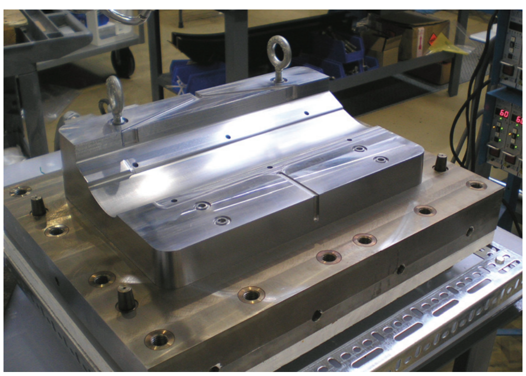
Full bracket insert



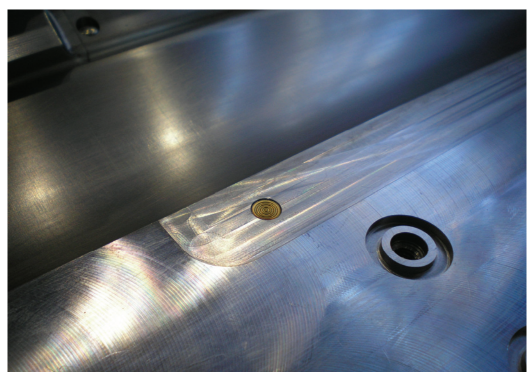
Upper insert



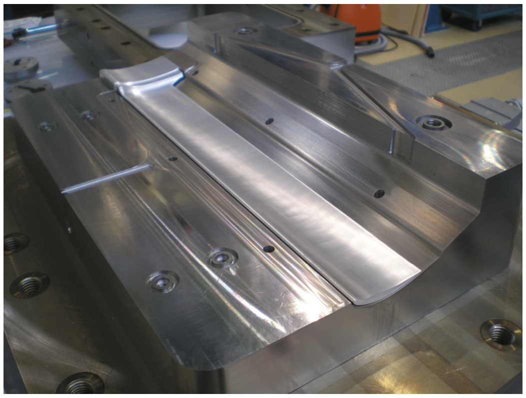
Lower insert being positioned onto modular mould cavity base plate (note six sensor holes passing through base plate and insert, also four cartridge heaters in base plate)



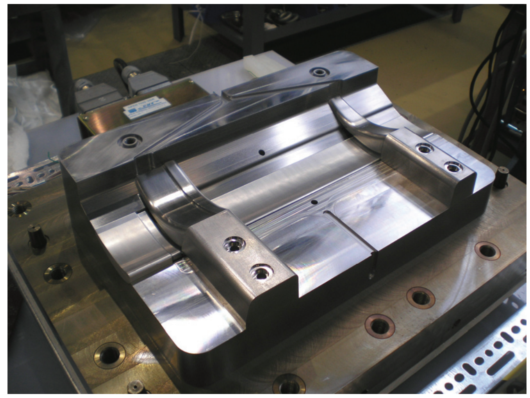
Lower insert in position (lifting eye-bolts not yet removed)



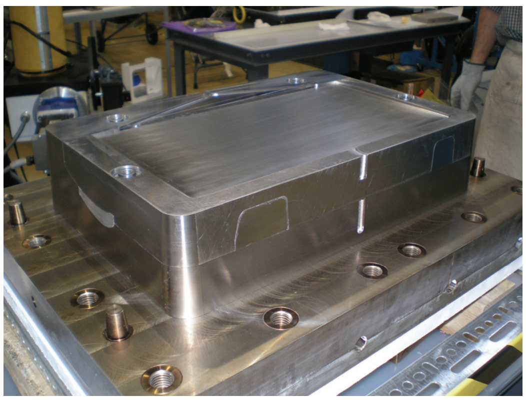
Close view of pressure sensor in lower insert (located at leading edge runner)



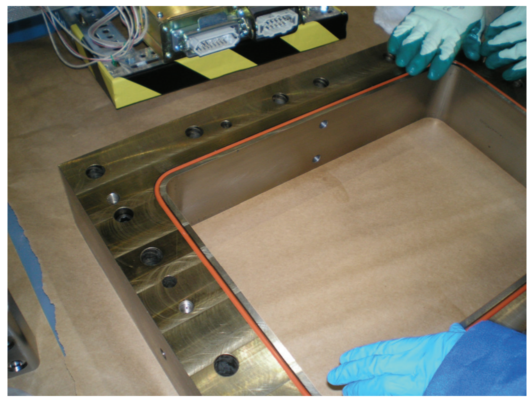
Aluminum mandrel positioned in lower insert



All inserts in position except upper insert (no preform)

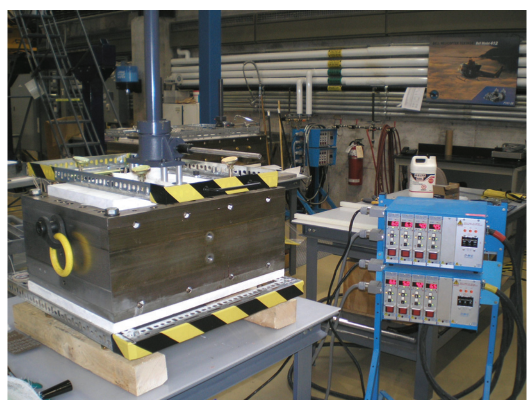


All mould inserts in position



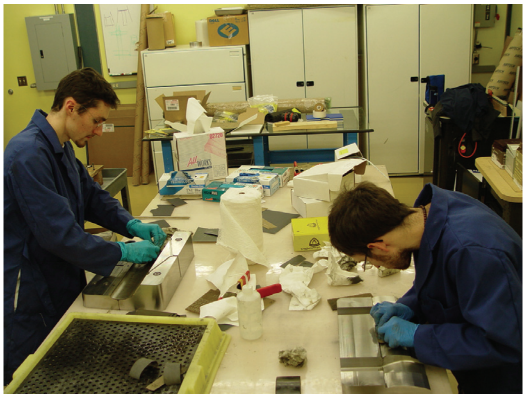
Modular mould cavity outer ring with o-ring installed

Modular mould cover (upper plate permanently bolted to outer cavity ring) with lifting piston extended (note hole in piston for dielectric sensor)

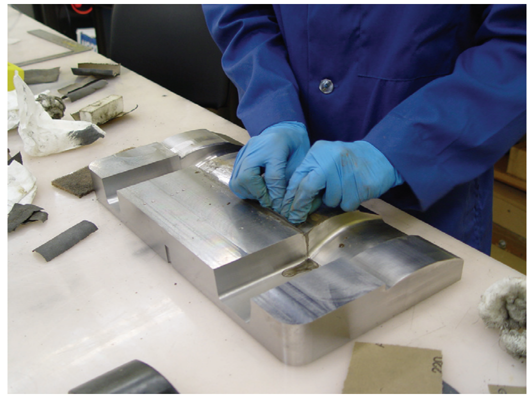


Mould fully closed, heater cartridge controller at right

Polishing

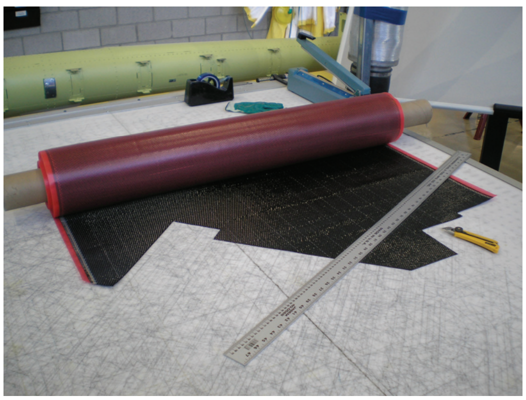


Polishing the lower and upper mould inserts

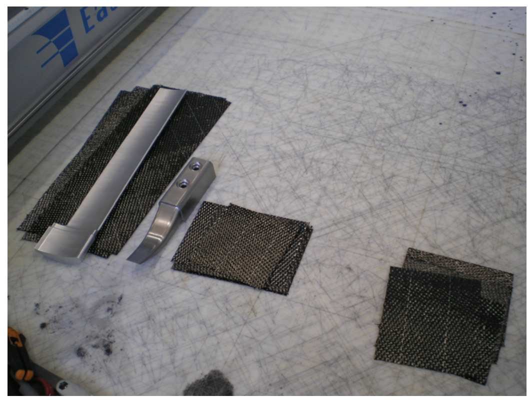


Polishing the upper insert

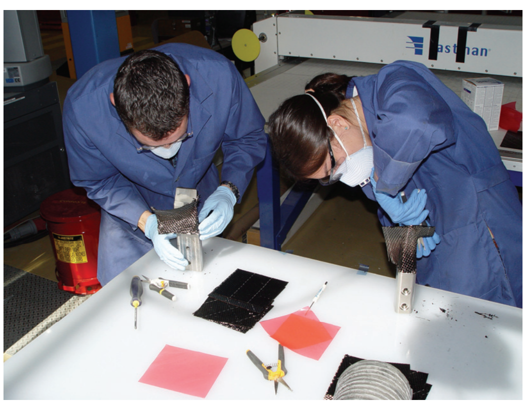
Preforming



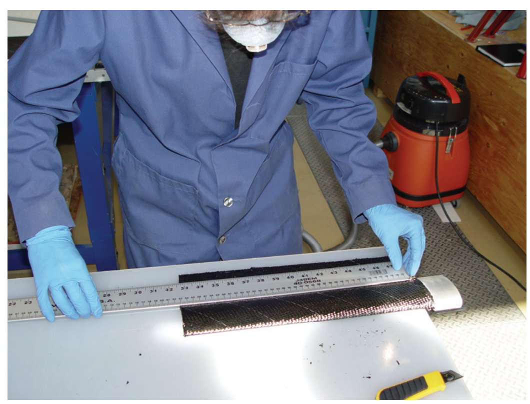
Roll of fabric



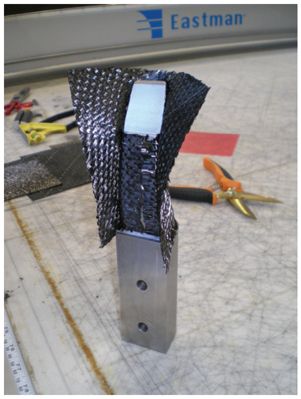
Pre-cut fabric squares used for prototypes 001-004



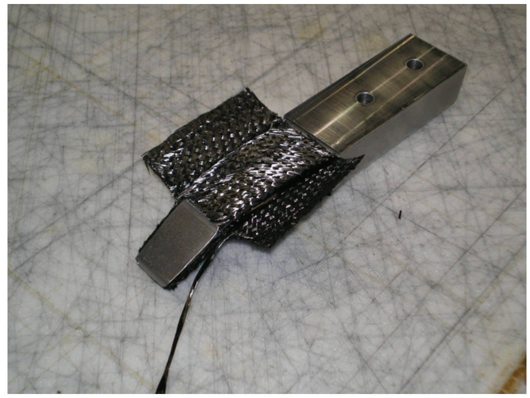
Fabric squares placed on inserts and trimmed by hand (prototypes 001-004)



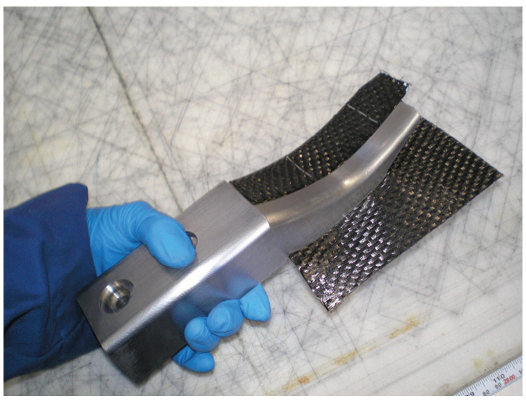
Ply dropoff measured onto airfoil trailing edge



Second ply positioned onto full bracket insert and ready to be trimmed by hand

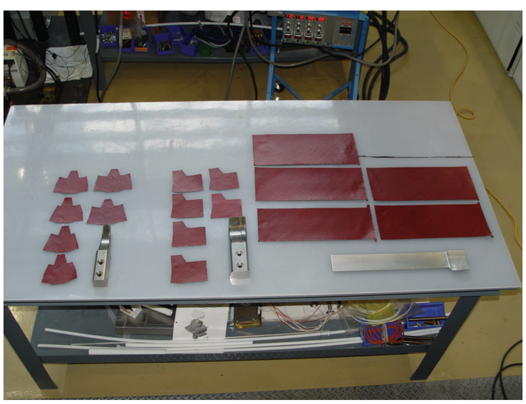


Unidirectional fibre filler ("noodle") being positioned on full bracket



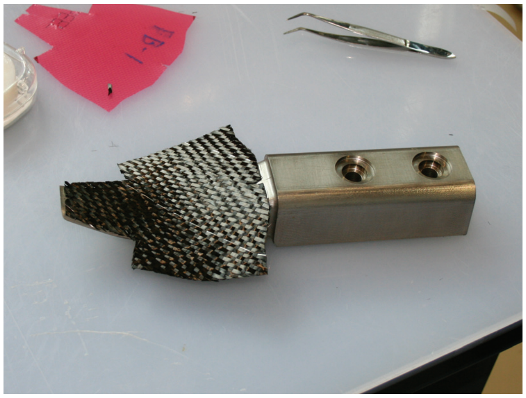
Half bracket plies positioned onto insert and ready to be trimmed by hand

Completed mandrel and half bracket (note ply dropoff visible on half bracket)

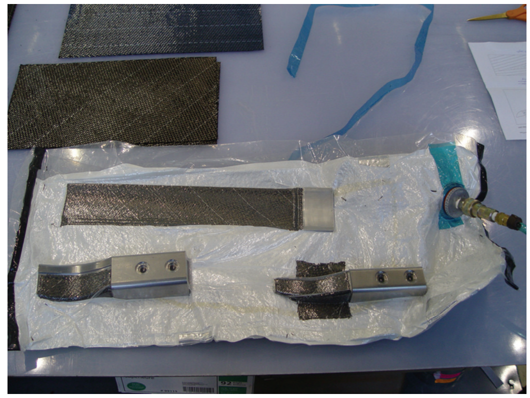


Exact preform patterns cut using automatic cutting table (for prototypes 005-008)

Positioning pre-cut patterns for each of the three slat components (full bracket, half bracket, and airfoil seen from left to right)

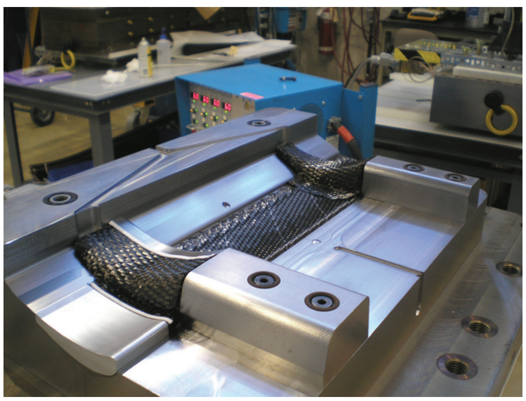


First pre-cut ply of full bracket positioned on insert (note notches used to centre the ply on the insert)

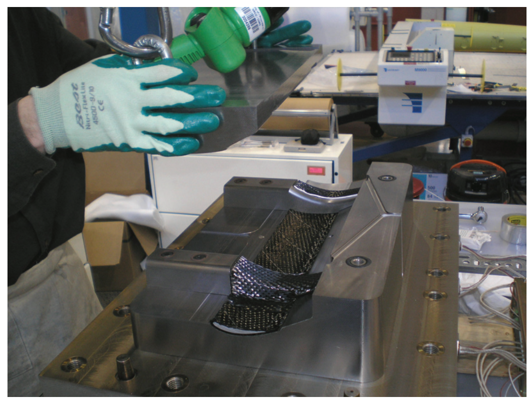


De-bulking the completed preform in a vacuum bag

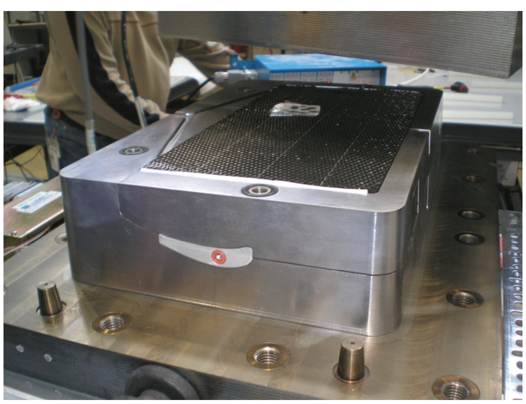
Preform loading



Preform loaded into mould (note expanded PTFE sealant along left end of airfoil and half bracket)



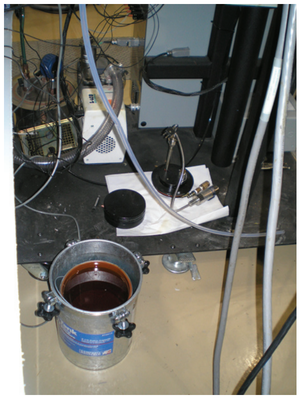
Upper insert being lowered into place using overhead crane

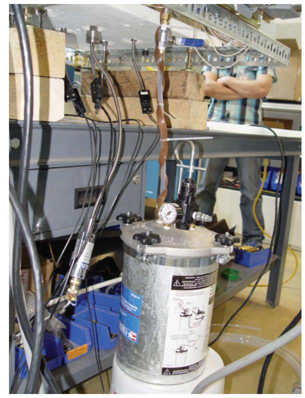


Witness coupon preform in place with expanded PTFE sealant along edge (note small o-ring around hole added to end of mandrel for extractor, and piece of fibreglass on witness coupon to insulate dielectric sensor in mould cover)

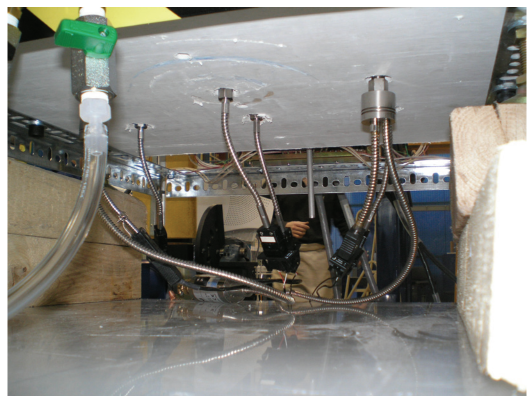
Modular mould cover being lowered into place using overhead crane

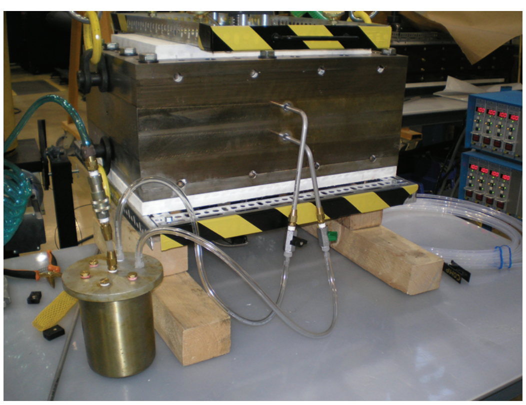
Injection hardware


Can of liquid resin in pressure pot


Resin line connecting pressure pot to mould heated with electric silicone heater blankets


Last portion of tubing running into mould is aluminum to withstand high temperature and pressure


Six mould sensors protruding from the underside of the mould

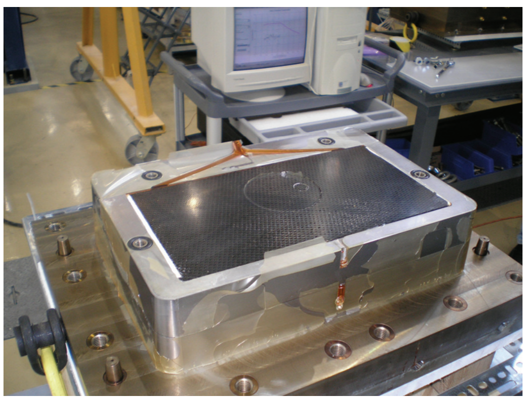

Two outlets connected to a catchpot and vacuum line


Bleeding resin from the mould ("burping") using valves on each outlet

Demoulding

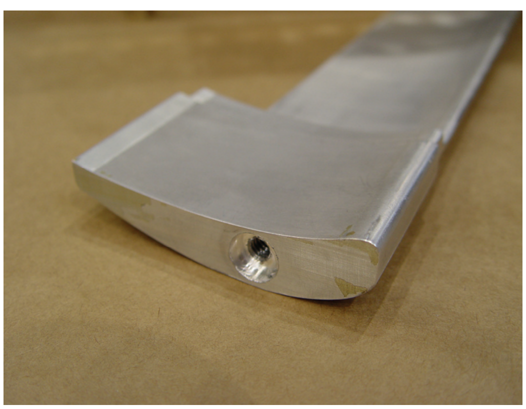
Screw jack used to extend piston in mould cover to break initial seal

Once seal is broken, cover lifted off with overhead crane

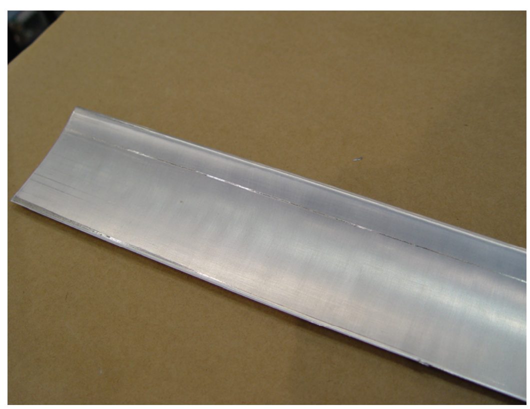


Cured witness coupon in mould

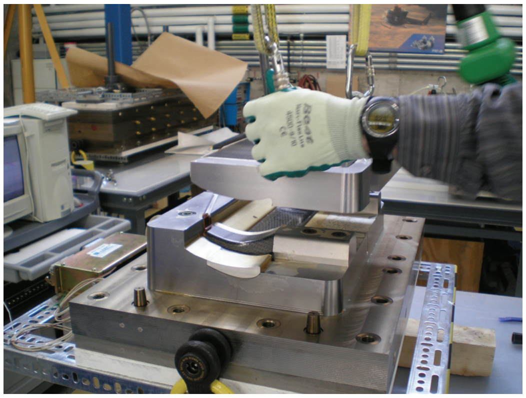
Mandrel extraction

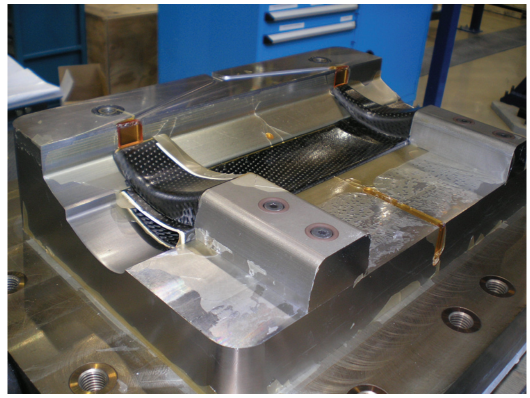


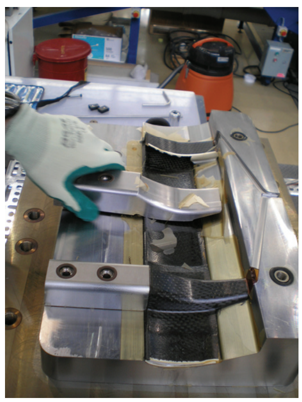
Threaded hole added to mandrel for extraction of eye bolt

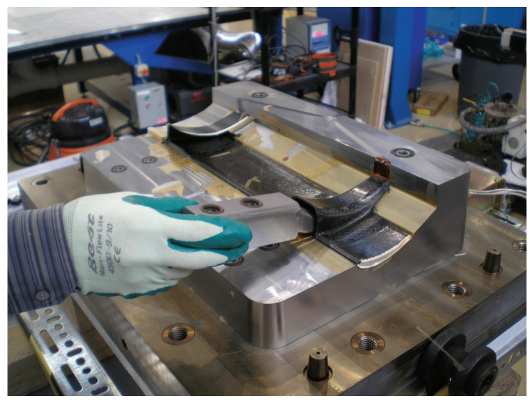


Typical scratches on mandrel after extraction

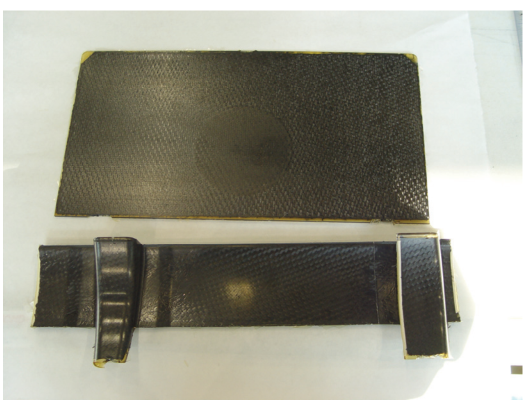

Upper insert lifted off with overhead crane

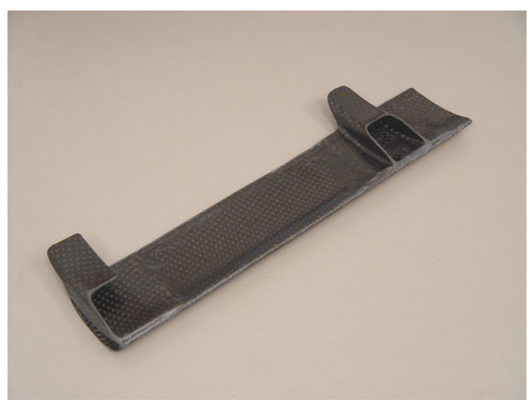

Cured part in mould


Half bracket insert removed by hand


Full bracket insert removed by hand

Completed Parts


Witness coupon plate and prototype slat as removed from the mould


Prototype 001 after trimming excess material