COUPLED DESIGN OF A HELICOPTER PART AND MOULD FOR RESIN TRANSFER MOULDING

Julian O'Flynn*, Marc-André Octeau**, France Thériault*, Larry Lessard*
*McGill University, **National Research Council Canada

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Abstract

A prototype leading edge slat for a helicopter horizontal stabilizer was produced by resin transfer moulding (RTM). The part was designed by considering manufacturability and stress analysis in parallel rather than sequentially. By taking an integrated approach to the design of this composite component, potential issues and conflicts could be resolved early in the process. Manufacturability issues considered included draft angles, ply dropoffs, and mould design. The stress analysis involved a finite element analysis (FEA) of the stabilizer assembly under load cases representative of various flight conditions. Finally, a prototype part was produced using a modular mould.

1 Introduction

Resin transfer moulding (RTM) is a process well suited to meet the growing demand in the aerospace industry to produce high performance parts at a reduced cost [1, 2, 3]. This paper presents an integrated approach to RTM by considering part performance and the manufacturing process in parallel rather than sequentially. Since mould design is generally considered the most critical factor in successful RTM [4], there is a particular emphasis on mould design here. Other perspectives presented include stress analysis, mould manufacturing, and part manufacturing. This multidisciplinary design approach provides an opportunity to integrate manufacturing constraints within the structure of the part thus reducing part count, assembly and tool complexity, and ultimately overall cost.

2 Project Description

A collaborative project between McGill University, École Polytechnique de Montréal, the National Research Council of Canada (Aerospace Manufacturing Technology Centre, Institute for Aerospace Research), Bell Helicopter Textron Canada, and Delastek Inc. is underway to develop an optimized design, analysis, and manufacturing process for composite materials made by RTM. The collaborative efforts for this project include part design, static and fatigue stress analyses, material characterization, injection simulation, process modelling, optimization techniques, mould design, and finally mould and part manufacturing.

The general goal of this project is to facilitate the design of structures made from composite materials by reducing manufacturing costs at the same time as improving the end product. By taking an integrated approach to RTM, development time for making parts can be reduced, properties can be improved, repeatability can be easier to achieve, and overall cost can be reduced [5].

The part selected as a technology demonstrator for this project is a composite version of a leading edge slat attached to the horizontal stabilizer of a helicopter (Figure 1). The one-piece composite part replaces an aluminum assembly composed of three airfoil segments and four attachment brackets plus hardware. The slat assembly is roughly 1 m long with a chord length of 75 mm and is connected to the horizontal stabilizer with eight fasteners. The slat airfoil and four brackets are to be moulded as a single piece to reduce part count and assembly steps. The eight-fastener attachment to the stabilizer remains for interchangeability with the existing assembly.

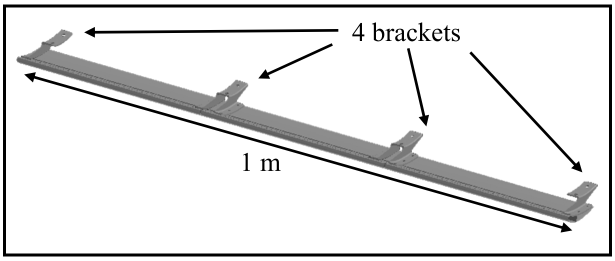

Fig. 1. Leading edge slat with attachment brackets

3 Coupled part and mould design

Part consolidation often comes at the expense of part complexity. In turn, part complexity is generally associated with a high tooling cost and difficult manufacturing process. It is therefore crucial to incorporate features that can simplify manufacturability early in the design phase of the part. Such features include preform simplicity, a minimum number of mould inserts, and ease of demoulding through large draft angles. Integrating these details during the design phase instead of during a subsequent manufacturability phase can significantly reduce the development time and cost, especially in RTM where design changes often require making a new mould [5].

Incorporating manufacturability features such as draft angles, ply drop-offs, and large corner radii early in the structural design not only reduces potential manufacturing conflicts but often improves the final part performance thus preventing the weight penalty of an over-designed part. For this project, these manufacturing details were therefore included in the stress analysis models from the start. The risks associated with issues such as moulding neat edges versus trimmed edges, close tolerances on the preform especially at ply drop-offs, and control of edge effects during mould filling were also considered.

4 Preliminary Manufacturing Considerations

The key manufacturing challenge in this project was to integrate the brackets with the airfoil such that the component could be produced in a single moulding operation. The integrated brackets resulted in a complex shape which was of concern for both stress analysis and manufacturing. A number of different metal bracket designs had been used in the past which included full brackets and half brackets in a variety of combinations and orientations. Three examples of possible bracket configurations are shown in Figure 2. The bracket configuration selected would most likely be symmetric as shown to allow interchangeability of the part for the left and right sides of the helicopter. The final choice between full and half brackets would be influenced by both stress analysis results and manufacturing considerations.

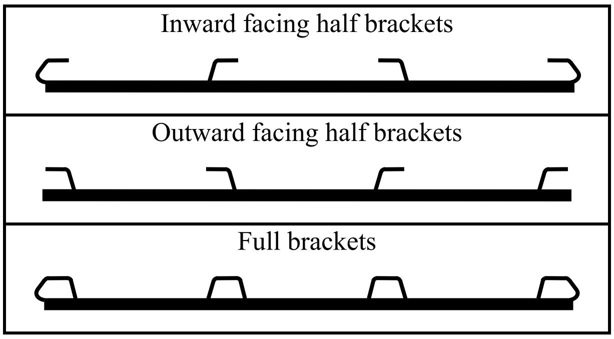

Fig. 2. Examples of possible bracket configurations

As with most composite designs intended to replace metallic parts, a direct copy of the metal design was not appropriate [2]. For example, the metal half brackets were attached to the airfoil with a single flange and fasteners (Figure 3). 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.

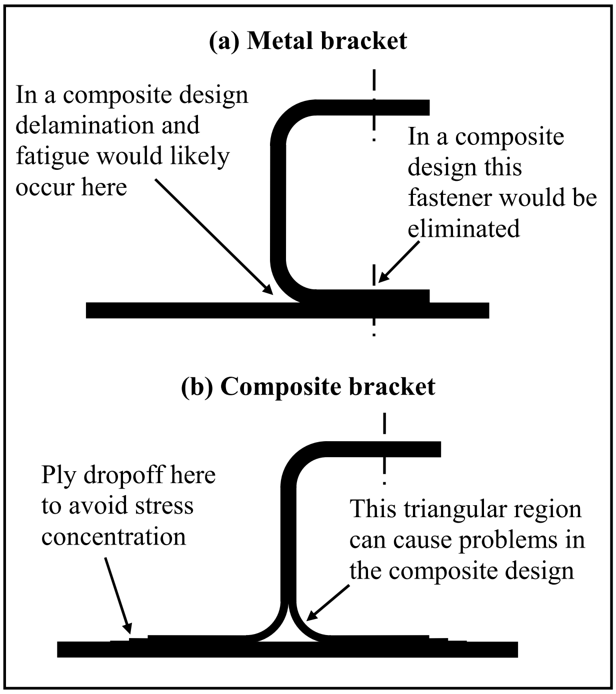

Fig. 3. Composite versus metal bracket design

From a manufacturing perspective, the triangular region at the bracket to airfoil intersection created by the composite redesign was not ideal (Figure 3b). If left as-is, this region would become resin-rich and a potential site for racetracking during injection and microcracking during cure [5]. The simplest solution was to fill the region with unidirectional fibre. However, an alternate bracket design was also proposed that eliminated this region entirely (Figure 4). The idea was to blend the bracket continuously into the airfoil, but this solution could only be applied to brackets located at the ends of the slat.

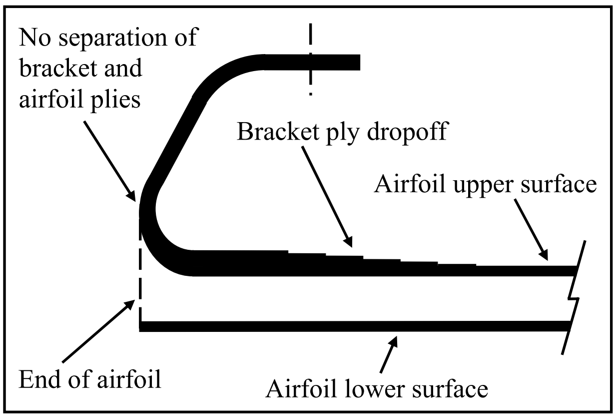

Fig. 4. Blended half bracket cross-section

To summarize, there are a total of four possible bracket types, as shown in Figure 5. 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 (not shown). This is due to space constraints on the flanges attaching the bracket to the airfoil.

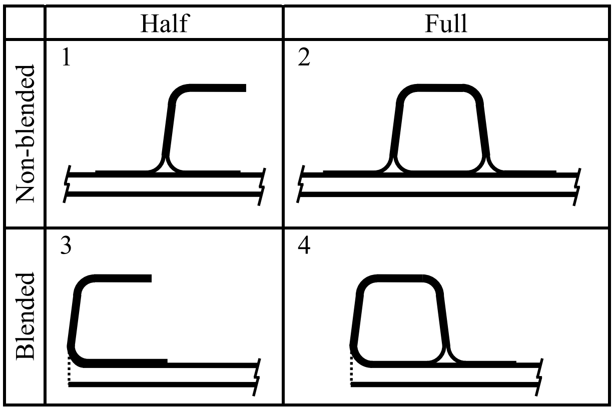

Fig. 5. Four possible bracket types

Another important aspect of manufacturing to consider was the post-machining stage. Although RTM has the potential to produce net-shape parts, it is sometimes easier to obtain clean part edges by adding excess material which can be trimmed off in a post-machining operation [6]. Figure 6 shows the result of adding excess material to all part edges.

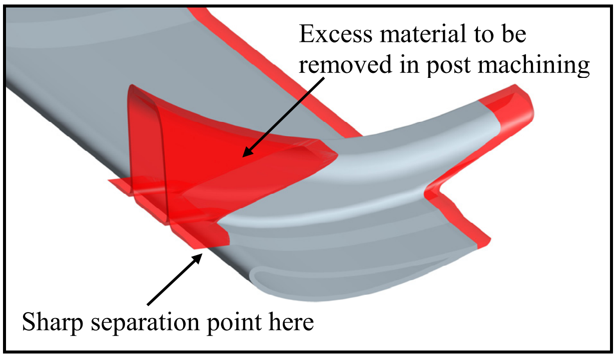

Fig. 6. Excess material along all part edges

However, as shown in the figure, a sharp separation point results where the leading edge of the brackets meets the airfoil. This sharp point was unacceptable for several reasons. The portion of the mould that fit into this point would be very fragile and therefore difficult to machine, handle, and demould. Also, removing all traces of this separation point in post-machining would be critical to prevent delamination and yet very difficult to achieve without damaging the airfoil surface.

A slight modification was therefore proposed in which the excess material at the leading edge of the brackets was tapered down to nothing at the bracket to airfoil interface (Figure 7). In addition, the trimming profile of the brackets was such that it arrived tangent to the airfoil surface at the bracket to airfoil interface to avoid damaging the airfoil surface. The drawback to this solution was that the leading edge of the bracket was now a neat edge at the bracket to airfoil interface which requires more precision in the preform.

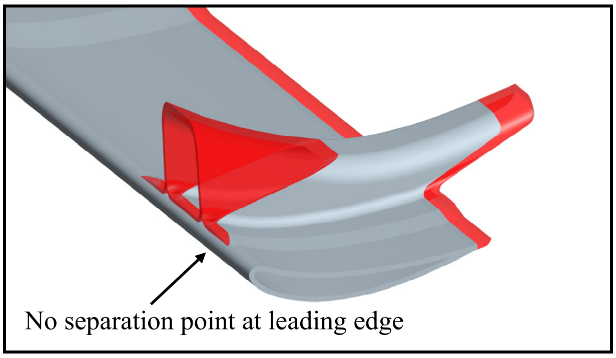

Fig. 7. Modified excess material design

5 Preliminary Stress Analysis

A preliminary stress analysis was carried out on the slat taking into consideration many of the manufacturing concerns presented above. The material selected for the part was a 5-harness satin carbon fibre weave with a one-part liquid epoxy resin system specially formulated with a low viscosity for RTM. This selection was based on mechanical property requirements, service temperature requirements, suitability for RTM, availability, and prior experience.

A comparative finite element analysis (FEA) was carried out using Patran/Nastran to help select the best bracket type. Both the stabilizer and the slat had to be modelled in order to adequately reproduce the complex loading and boundary conditions of the flight environment. Due to the symmetry of the slat and stabilizer assembly on either side of the helicopter, only the left hand side assembly was modelled.

Boundary conditions and load cases representative of various flight conditions and manoeuvres were applied to the assembly. Boundary conditions were critical to obtaining realistic results, particularly at the stabilizer to slat bracket attachment fasteners. Shell elements were used to model the composite lay-up of the slat. The Tsai-Wu quadratic failure criterion was chosen since it is one of the simplest and widely used failure criteria for anisotropic materials [7].

The three bracket configurations shown in Figure 2 were tested in the analyses. From the preliminary results, it was found that there was little difference between the configurations. However, half bracket configurations are more flexible and are a better choice from a material savings and ease of processing perspective.

For all cases, the most critical stress concentration areas were located around the fastener holes and the bracket radii (Figure 8). Based on these preliminary results, a lay-up was proposed consisting of 4 plies for the airfoil and 6 plies for the brackets.

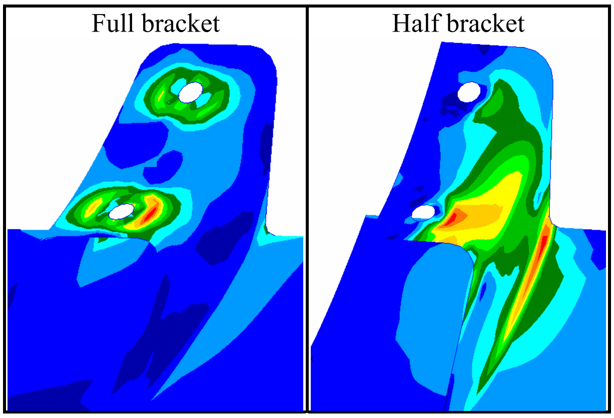

Fig. 8. Sample FEA results showing stress concentrations at bracket holes and radii

6 Prototype Design

In order to verify the manufacturability of the slat designs without investing in a large mould, a half-length prototype slat was manufactured with two brackets instead of four (Figure 9). Since the preliminary stress analysis did not indicate a clear preference for bracket type, a blended half-bracket (Figure 5, option 3) and a non-blended full-bracket (option 2) were selected to determine the viability in production of these complex geometries. The prototype also provided an opportunity to troubleshoot the manufacturing process, including mould machining, preforming, injecting, and curing.

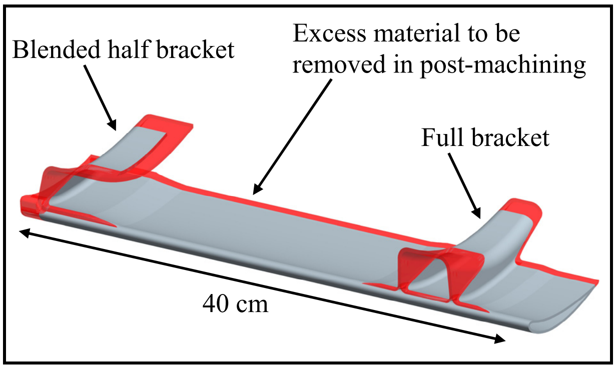

Fig. 9. Prototype slat

Both the prototype and full-size parts for this project were to be made using pre-existing modular mould cavities. The modular mould concept provided a cost effective means of producing a self-contained RTM mould [8, 9]. The majority of complex mould features such as clamping, heating, sealing, and interfacing with the injector were all built into the re-usable cavity. Moulding a part simply required a set of inserts to be machined that defined the geometry of the part and contained appropriate resin channels.

The modular mould cavity used for the prototype slat was roughly 100x300x460 mm (4x12x18 inches). It consisted of a cavity ring with upper and lower plates (Figure 10). Each plate had four embedded electric cartridge heaters. An o-ring between each plate and the cavity ring ensured an air-tight seal within the mould cavity. Holes in the sides of the cavity ring could be used as resin gates or vents.

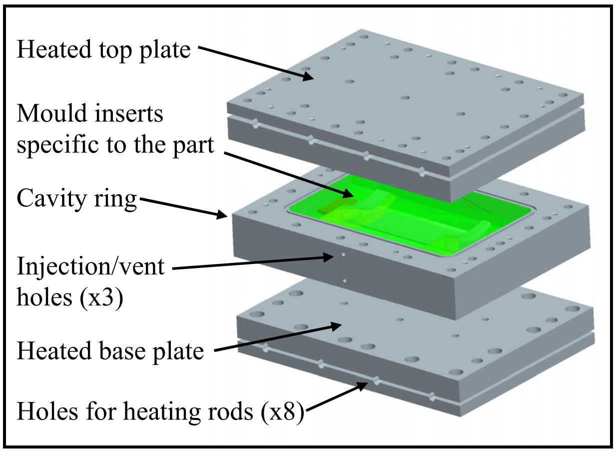

Fig. 10. Modular mould

A set of inserts for the prototype slat was machined by Delastek Inc. from P20 tool steel chosen for its low coefficient of thermal expansion. The inserts were designed to produce not only the prototype part but also a "witness" coupon plate simultaneously in the same mould (Figure 11). Material from this plate could be used to perform mechanical tests and verify the processing conditions.

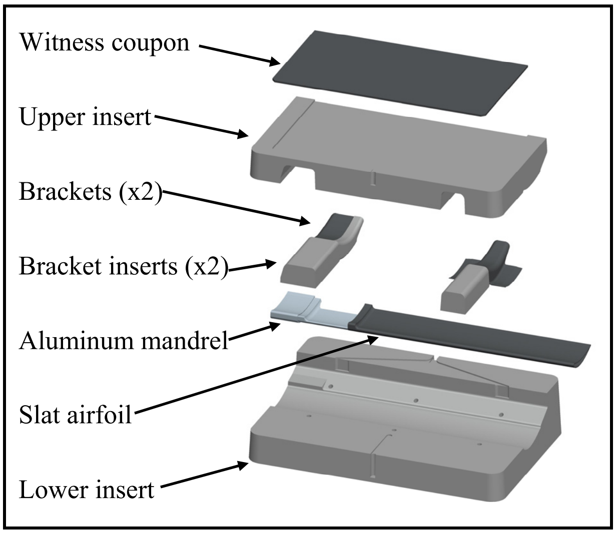

Fig. 11. Mould inserts for prototype slat

As expected, the integrated brackets provided the main challenge in designing the mould inserts. Regardless of type (full or half), the brackets created "trapped" regions of the mould which made a simple two-piece mould design with a single parting plane unfeasible. Separate inserts were required to fit under each bracket. The geometry of these inserts had to be designed considering the preforming sequence, demoulding sequence, ease of machining, and durability in a production environment. For example, solid modelling with motion analysis was used to ensure that the full bracket insert could be removed without any interference.

The hollow airfoil of the slat also posed a mould design challenge. An internal bladder and a solid mandrel were both considered as options. The internal bladder would be easier to demould and more forgiving of any inconsistencies in preforming, for example at ply dropoffs. However, a solid mandrel would make preforming easier and avoid the complications of passing air lines into the mould. The solid mandrel option was selected for the prototype to determine its viability. Unlike the other mould inserts that were made of tool steel, the mandrel was made of aluminum. Its greater coefficient of thermal expansion could be used to help in demoulding. Note that a thermal "shrink factor" was applied to all the mould inserts based on their coefficients of thermal expansion [10].

The complex geometry of the part resulted in difficulties both designing and machining the mould inserts. The problem was not only to facilitate manufacturability of the composite part, but within this context to also design the mould itself for manufacturability. Collaboration with the machining facility was crucial at this stage in the design process. Some of the important lessons learned included: pieces should be designed to be machined from as few sides as possible, have as many flat and perpendicular surfaces as possible for clamping and referencing, and avoid sharp edges and undercuts.

Flow modelling of the prototype and full-size part was performed by École Polytechnique de Montréal. The flow modelling was carried out concurrently with the part and mould design to identify potential problems as early as possible. 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 12).

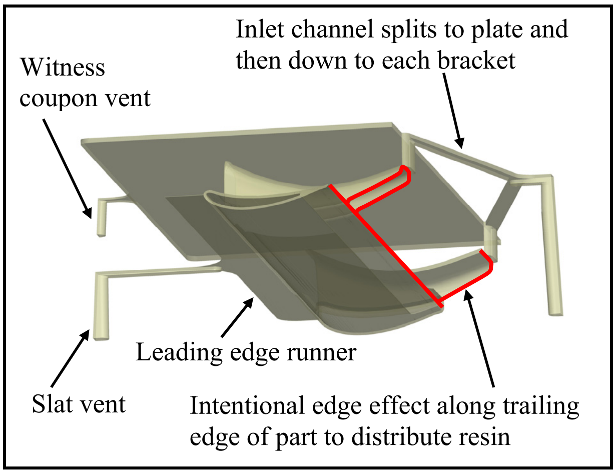

Fig. 12. Mould cavity to be filled

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 0.254 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 two 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.

7 Prototype Manufacturing Trials

RTM injections were carried out using a pressure pot system. The resin and mould were preheated to 80ºC for the injection. Figure 13 shows the preform in the mould before injection. Mould filling times were on the order of 10 minutes. Injection pressure was ramped up to 240 kPa (35 psi) during mould filling and then increased to 310 kPa (45 psi) after closing the vents to ensure complete wetout and to minimize voids [6, 11]. The mould temperature was then ramped to 180ºC at 1ºC per minute and held at this temperature for 2 hours for a complete resin cure.

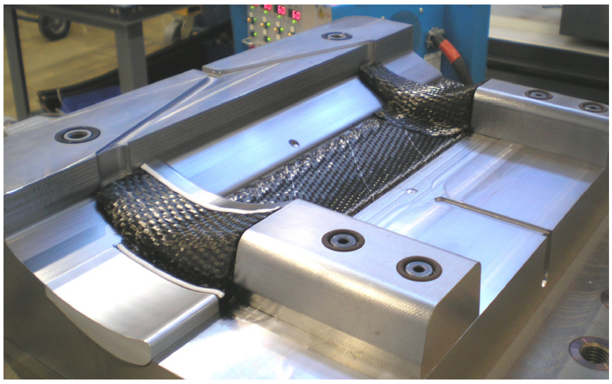

Fig. 13. Preform in the mould

The mould was allowed to cool to 100ºC before demoulding. The temperature was kept as high as possible to minimize stresses from thermal contraction of the mould yet low enough to allow safe handling of the inserts. Demoulding posed no major problems. The bracket inserts could be removed easily by hand while the mandrel was pulled out using a mandrel extractor. Figure 14 shows the part in the mould after cure.

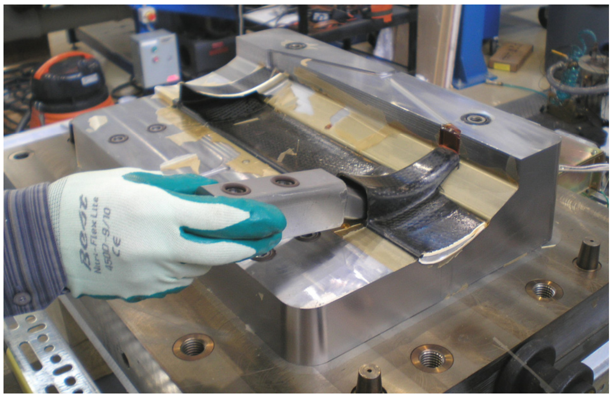

Fig. 14. Removing the full bracket insert after cure

Finally, the part was trimmed and sanded by hand to the final dimensions. The finished prototype is shown in Figure 15.

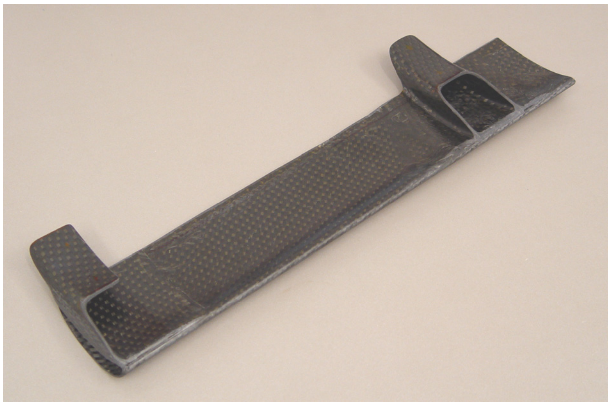

Fig. 15. Trimmed prototype slat

8 Conclusions

A concurrent design approach was taken to produce a helicopter component by resin transfer moulding. By considering manufacturability and stress analysis in parallel rather than sequentially, any issues and conflicts could be resolved early in the process. This greatly reduced the potential for costly redesigns at later stages in the project.

The part being considered for this project was the leading edge slat on the horizontal stabilizer of a helicopter. An assembly of metallic brackets, airfoils, and fasteners was consolidated into a single composite component. The complex geometry of the integrated brackets resulted in a challenging mould design with multiple inserts.

To demonstrate the feasibility of the designs being considered, a half-length prototype slat with two different bracket designs was produced. Results of the prototype fabrication showed no problems for manufacturing either of the bracket types selected for the prototype. In addition, a solid mandrel was used successfully for the airfoil which greatly simplified performing and the mould design compared with an internal bladder. Future work will consist of applying the lessons learned from the prototype to the design, optimization, production, and testing of a full-size slat.

Acknowledgements

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