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Developments of Resin Transfer Moulding Technology at NLR

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ABSTRACT

Resin Infusion techniques like Resin Transfer Moulding (RTM) for fibre reinforced composites are among the more recent fabrication technologies with potential for weight and cost reduction, that are being introduced in the aerospace industry. The present paper focuses in particular on the technology for closed moulding, pressurised RTM. This technique results in products with high dimensional accuracy, is applicable to thick parts of complex shapes, and allows a high level of part integration and (preform) automation.

Over the last decade, the National Aerospace Laboratory NLR in the Netherlands has contributed to this technology, with the following application driven research projects:

Nationaal Lucht- en Ruimtevaartlaboratorium
National Aerospace Laboratory NLR

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INTRODUCTION

Resin Infusion techniques like Resin Transfer Moulding (RTM) for fibre reinforced composites are among the more recent fabrication technologies with potential for weight and cost reduction, that are being introduced in the aerospace industry. The present paper focuses in particular on the technology for closed moulding, pressurised RTM. This technique results in products with high dimensional accuracy, is applicable to thick parts of complex shapes, and allows a high level of part integration and (preform) automation.

Over the last decade, the National Aerospace Laboratory NLR in the Netherlands has contributed to this technology, with the following application driven research projects:

- Bracket for the Ariane launcher
  In this project, techniques for preform manufacturing like stitching and bindering were evaluated. Also, design rules for concentrated load introduction were developed
- Torque link for the NH90 landing gear In this project, process specifications were developed, tooling design and design for affordability was addressed
- Trailing arm for the NH90 landing gear
  Injection strategies were developed, exothermal peaks were dealt with, process monitoring was developed, and automated preform techniques and simulation were developed
- Integrated beam concept
  In this project, the integration of brackets as well as net shaped fabrication issues were addressed
- Drag Brace for the F-16 landing gear This project resulted in the first flying article, for which certification and quality assurance issues were addressed
- TANGO-frames for an A320 sized aircraft
  In this project, in which a large series of fuselage frames were manufactured, the issue of high production rates was addressed.

The present paper presents an overview of the results of all these projects.

BRACKET FOR THE ARIANE LAUNCHER

In order to investigate the feasibility of RTM for the fabrication of complex shaped composite components with concentrated load introductions, a technology programme was carried out in which an existing metal bracket for the Ariane V launcher was redesigned in composite materials. The main objective was to realise a substantial weight reduction by replacing aluminium by composites. The composite bracket was designed with the finite element code B2000, which is in use at NLR as a test bed for developments in computational mechanics. It was decided to keep the interface between the backing structure the same as for the metal bracket, in order to make a retrofit possible. However, the general layout of the bracket was allowed to be different from that of the metal bracket. The composite bracket was optimised for minimal weight with the optimisation module B2OPT within B2000. This optimisation code minimises the weight of the bracket while the design is subjected to constraints on stresses. In order to design the pin-loaded holes, generic composite specimens with concentrated load introductions were manufactured and tested. These specimens differed from each other by geometry and by laminate architecture.

The test results were used to derive general design stress levels (bearing stress, shear-out stress and net section tension stress) for pin-loaded holes, which were used to design the pin-loaded holes of the composite bracket. These values were used as side constraints for the optimisation. These side constraints were set to values that ensured a bearing failure mode, since this failure mode has a fail-safe character.

Since the composite bracket had a complex shape, it was decided to develop a modular sub-preform concept. In order to manufacture these sub-preforms, the stitching and bindering, preforming concepts were evaluated. Stitching turned out to be very cumbersome and time consuming whereas bindering was very easy. The bindering concept is based on applying a binder powder (approximately 4% of the weight of the preform) to the individual layers of the preform. The preform then is placed onto a template after which the preform is heated while vacuum is applied to the preform. After cooling down, the preform is stabilised. The big advantage of this concept was that in combination with a binder technique these sub-preforms could be made relatively easily and nearly net-shaped. Assembly of the sub-preforms into the RTM mould therefore was simple. Several brackets were manufactured successfully (see fig. 1). The brackets had a fibre volume fraction of 55%.

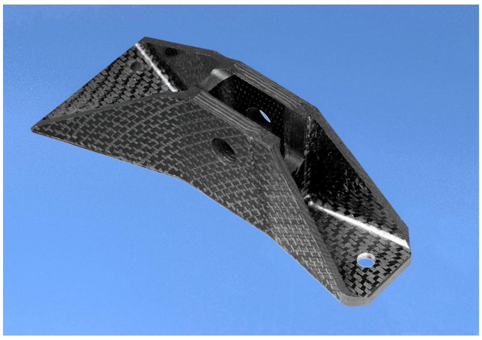

Figure 1: Composite bracket for space applications

In comparison to the aluminium bracket a weight reduction of 43% was achieved. All brackets were tested statically to 1.4 x Design Ultimate load without failure.

TORQUE LINK FOR THE NH-90 LANDING GEAR

In landing gear applications a torque link is used to prevent the landing gear from shimmying during landing operations. Like the aluminium counter part, the composite torque link was composed of two elements: an upper torque link and a lower torque link, which were different by geometry.

The composite torque link was developed in the framework of a landing gear technology programme in collaboration with the following partners: SP aerospace and vehicle systems, MSC Nastran, Eurocarbon and NLR. For this component, SP aerospace and vehicle systems delivered the specifications and assisted during the preliminary design phase, MSC Nastran carried out finite element calculations. Eurocarbon developed an automated preforming technique by using the over-braiding concept. NLR made the preliminary design, developed the preforming and RTM tooling concept, fabricated several torque links and carried out static tests. These static tests included damage tolerance tests on torque links with impact damages.

The torque link was designed in a way that both the upper and the lower element could be manufactured in the same RTM mould in order to limit tooling costs. Since the composite torque links were designed for minimal cost, they were configured without a shear web (which would be the optimal solution from a strength and stiffness point of view). Due to the absence of the shear web several torque links could be manufactured simultaneously by producing the torque links as a beam. After curing, this beam was machined into six slices. Figure 2 presents a torque link after machining.

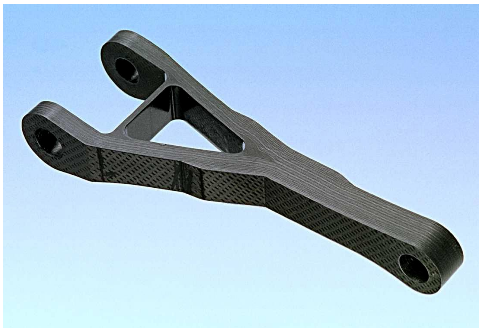

Figure 2: Torque link after machining

Several torque links were manufactured successfully and were inspected by C-scan. The fibre volume fraction of the torque links was 58%. In comparison to the weight of the aluminium torque link, a weight reduction of 29% was realised. Before being tested, metal bushes were mounted in the holes needed for load introductions.

In order to demonstrate sufficient damage tolerance, several torque links were damaged by applying Barely Visible Impact Damages prior to testing. All torque links were tested statically and failed beyond their design Ultimate Load Level.

TRAILING ARM FOR THE NH90

After the successful demonstration of the feasibility of composites in torque link applications, the next step in the landing gear technology programme was to develop a more complex and highly loaded element. For this purpose the trailing arm of the NH90 was selected. The trailing arm is one of the major elements of the main landing gear of this helicopter (see fig. 3).

Figure 3: Location of the trailing arm in the main landing gear.

The metal reference trailing arm is made by machining a high strength steel forging. This machining operation is very time consuming, which makes this component a very good candidate for realising a reduction in manufacturing costs and a reduction in lead time by using composites.

The main objective was to realise a cost and weight saving and to reduce the lead time by 20% in comparison to this metal reference.

The final composite trailing arm assembly consists of a tubular braided element, two composite tubes with bronze bushings, a central lug made of fabric and a steel wheel axle (see fig. 4).

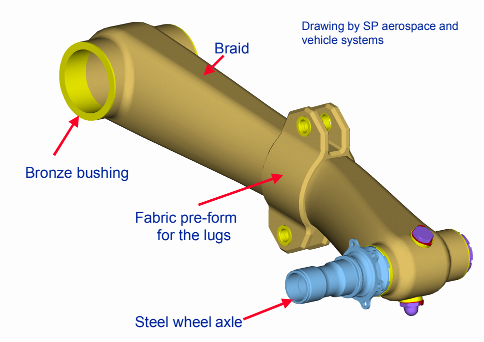

Figure 4: CAD drawing of the trailing arm after assembly.

In order to realise the savings in cost and the reduction in lead time, automated preforming concepts with a high level of part integration were developed.

The fabrication process can be described as follows. In the first phase of the process, two cured composite pre-preg tubes were bonded to a tin-zinc melting alloy core. Then this core was positioned into a braiding machine. The over-braiding technique was used to apply a number of tri-axial layers onto this core (see fig. 5).

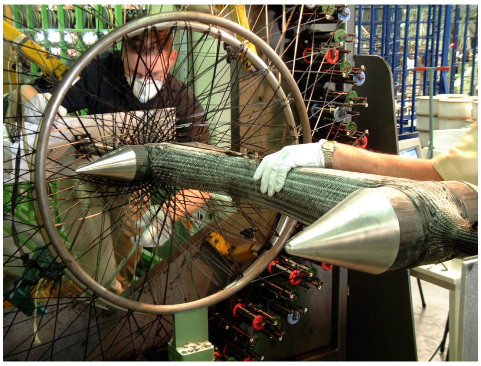

Figure 5: Applying fibres to the core by using the over-braiding technique at Eurocarbon.

During the development of the automated overbraiding concept it became clear that it was very difficult to predict the fibre orientations in the preform as a function of the braiding machine settings. However, these fibre orientations had to be known in detail in order to be able to predict the stiffness of the final component. It was therefore decided to start a research programme together with the University of Twente. In this research programme a braiding simulation tool is being developed. With this simulation tool, the fibre orientations as a function of braiding machine settings can be predicted. However, the simulation can also define the required machine settings on the basis of the desired fibre orientations. With this tool the development time and development costs of a braided preform are reduced dramatically. This will increase the competitiveness of braided preforms for tubular RTM components as replacements of metal forgings.

Parallel to this braiding process, a net shaped preforming process was developed for making the sub-preforms of the lugs. These preforms were made, using the binder powder technique. As mentioned earlier, this technique enables nearly net-shaped preforms, which are very robust and are easy to handle (see fig. 6).

Figure 6: Net-shaped preforms for the lug area of the trailing arm using binder technique.

After finalising the braided preform and the preform for the lugs, both preforms were positioned into an aluminium oil heated tool. Aluminium was selected as tooling material since aluminium had the same coefficient of thermal expansion as the melting alloy in the core. Once the RTM tool was heated to the required temperature, resin was injected. In order to determine the optimal injection strategy (short injection time and minimal risk for entrapped air) RTM flow simulations were carried out for which RTM Worx was used. On the basis of the flow simulations two resin inlet points at the ends of the trailing arm and four ventilation points (needed to evacuate the air during resin injection) near the lug areas were defined.

The thickness of the composite trailing arm was approximately 17 mm. Processing tests with the RTM resin used, demonstrated that during the cure phase an exothermal peak was likely to occur. In order to deal with this exothermal peak during curing, extensive temperature measurements were carried out during the curing phase, by measuring the temperature at several locations in the RTM mould and inside the low melting alloy core. These temperature readings were used to control the oil-heating unit. As a result, the oil unit successfully cooled the tool during curing in order to keep the resin temperature within the allowable temperature range.

After curing the resin, the trailing arm was released from the mould. Then the trailing arm was post-cured in an oven. During this post-cure, the low melting alloy melted out, was collected and could be used for the next trailing arm. A fibre volume fraction of 58% was realised. Figure 7 shows a composite trailing arm after assembly of the steel wheel axle and the wheel. The weight reduction achieved was 20%. The reduction is lead time was more than 20%. A number of additional composite trailing arms will be manufactured and these will be tested in a landing gear test rig located at the test centre of SP aerospace and vehicle systems.

Figure 7: Composite trailing arm after assembly

INTEGRATED BEAM CONCEPT

In the framework of a next generation fighter development programme, a thick doubly curved composite beam with an integrated bracket was developed. The main objectives of this programme were to develop net shaped preforming concepts with a high level of part integration using Non-Crimped fabrics. Figure 8 presents the composite beam after machining of the holes in the bracket.

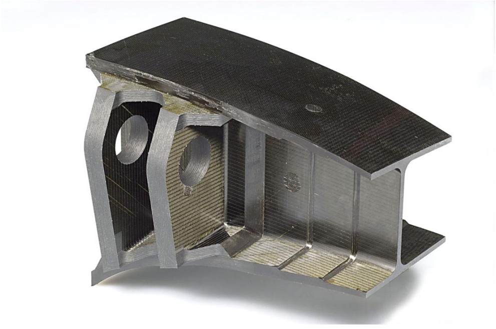

Figure 8: Composite beam with integrated bracket.

The composite beam was made in one single RTM cycle, hence eliminating assembly costs of the bracket to the I-beam. The only machining required was the machining of the holes in the bracket and the trimming of the edges of the vertical webs of the bracket. The main challenge was to develop a preforming and manufacturing concept that would not exceed the cost reduction gained by minimising assembly, trimming and machining efforts.

Therefore, low cost preforming tools for the bracket and the beam were developed. With these preforming tools, bindered layers of non-crimped fabric could be preformed to net shape (including the thickness) in an oven while applying vacuum to the preforms. Since the thickness of both preforms could be controlled very accurately, (due to the binder powder the preforms were very stable), assembly of these sub-preforms was very easy.

After being positioned into a steel mould the mould was heated to the required temperature. Since the coefficient of thermal expansion of the steel mould differed from that of the carbon fibre preform, small gaps occurred between the edges of the preform and the tool. This would lead to unfavourable race tracking during injection. This problem could not be eliminated. Therefore RTM flow simulations were carried out in which these gaps were modelled in detail in order to carry out a simulation with race tracking effects. These flow simulations were used to determine the most robust injection strategy. This strategy was used to manufacture one beam with an integrated bracket successfully. The fibre volume fraction achieved was 58%. The outcome of this programme was used to develop a parametric cost model for RTM components that can be used during trade studies.

F-16 DRAG BRACE

In the framework of the NVJSF technology programme, the feasibility of composites in heavy loaded landing gear components was investigated. This programme was carried out in close collaboration with SP aerospace and vehicle systems. As technology demonstrator the drag brace of the main landing gear of an F-16 was selected since this component is one of the main load carrying elements of the main landing gear. The most important specifications for the composite drag brace were:

- The drag brace should fit in an F-16 landing gear, since flight testing was part of the technology programme
- The maximum allowable weight was 80% of the weight of the original high strength steel component
- The drag brace should remain operable after impact from runway debris up to 86 Joule
- The drag brace should be able to operate at 73 ^{0}C and 85% relative humidity
- The chemical resistance of the materials used should be high.

During the conceptual design phase, the lugs with the concentrated load introductions were designed with in-house design rules. A box girder concept (the steel reference drag brace was an I-beam concept) was selected since a box girder has few free edges, as these are sensitive to impacts. Resin Transfer Moulding was selected as fabrication method due to the complex shape and the high thickness of the drag brace. A fabrication concept was developed that was capable of manufacturing three drag braces per day. For this purpose, an RTM carrousel concept was developed which consisted of relatively simple multiple inner moulds without heating, to make pre-forms, and one more complex heated outer mould to inject the resin. Since flight-testing was part of the demonstration programme, quality assurance during component manufacturing was extremely important. Therefore an RTM process monitoring system was developed. The RTM process monitoring system recorded the most important RTM process parameters during resin injection such as: temperature profile of the mould, resin flow, temperature of the resin inside the RTM machine and injection hoses and injection pressure as a function of time. Several composite drag braces were manufactured successfully (see fig. 9). The weight target of 20% weight reduction was easily met, since a weight reduction of 39% was achieved.

Figure 9: Composite drag brace

The RTM process monitoring system demonstrated reproducibility of the RTM process. Prior to flight testing, several composite drag braces were tested statically and in fatigue. All tests were carried out successfully. During the static tests the components failed beyond the required load level and during the fatigue test, the no-growth concept for delaminations was demonstrated.

On the basis of the reproducibility of the manufacturing process and the test results on component level, flight clearance was given. Therefore, one drag brace was assembled in an F-16 of the Royal Netherlands Airforce (see fig. 10) and successfully flight-tested (see fig. 11).

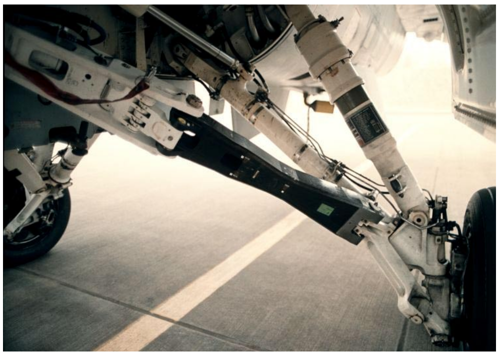

Figure 10: Composite drag brace after assembly in the F-16 main landing gear

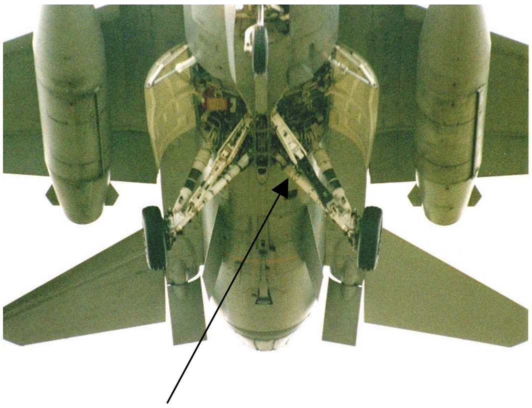

Figure 11: Composite drag brace during flight-testing.

TANGO COMPOSITE BARREL FRAMES

In the European Union Framework V project TANGO (Technology Application to the Near-Term Business Goals and Objectives), a full composite fuselage was developed. NLR was responsible for manufacturing composite frames for this fuselage. The composite barrel had a diameter of 3.95 meter.

The composite frames had to be manufactured within very tight dimensional tolerances:

- Radius: 1975 mm –0.0 mm, + 1.5 mm
- Angle between web and flange: 90^0 +/-0.25^0
- Thickness control: 3.6 mm +10%, -5%.

Due to these strict dimensional requirements RTM was selected as fabrication method. As fibre reinforcements, non-crimped fabrics in combination with spiral fabrics were selected.

A risk analyses was carried out, in order to determine whether the frames could be made as a single component or that the frames should be composed of several segments. The outcome of the risk analysis was that the frames should be composed of several segments. This was due to the high risks involved with handling large preforms for full frames. Also the risk for high scrap rates when using a full frame RTM tool were considered high, due to the mismatch in coefficient of thermal expansion of the metal tool and the composite frame. This risk could be minimised by using an Invar RTM tool. However, from a budgetary point of view this was not feasible. It was therefore decided to build up the frame of four segments. The thickness of the frames was 3.6 mm. All four frame segments were different in geometry due to the change in height of the web (height of the web varied between 92 mm and 124 mm) and due to the presence of a joggle in the window area.

The frames had to be manufactured in a short time span. In order to limit tooling costs and meet the delivery dates, an RTM carrousel tooling concept was developed. This tooling concept was based on four relatively simple preform tools and one RTM mould (see fig. 12) all of which were made of steel. The preform tools were used to laminate the individual preform layers. After laminating, this preform tool was placed inside the RTM outer mould, which was oil heated. After closure of this outer mould the temperature of the tool was increased to the required injection temperature and resin was injected into the preform. Resin was injected through a central injection point, which was transferred to an injection line in order to inject the resin through the outer radius of the frames. In order to avoid resin race tracking, the ends of the preforming tools were sealed by silicon blocks.

During the curing phase the next preform could be prepared in the following preform tool. In this way a very efficient RTM carrousel concept was generated.

Figure 12: RTM carrousel showing two preform tools and the oil heated outer RTM tool.

The fibre volume fraction of the frames was 60%. After curing mouse holes were machined into the frames and the dimensional tolerances were checked. All frames met the requirements. Figure 13 presents an overview of the four different frame segments.

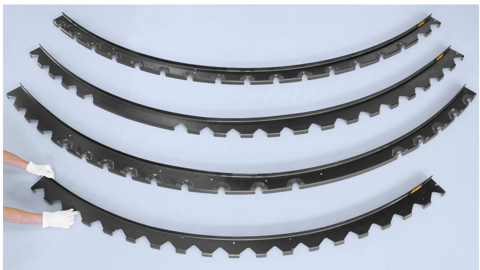

Figure 13: Four different composite frame segments after machining the mouse holes.

CONCLUSIONS

The present paper presents an overview of the developments of RTM as fabrication method at the National Aerospace Laboratory NLR. This overview shows the potential of RTM as fabrication method for cost effective composite components. The projects served to provide the Dutch aerospace industry with knowledge on RTM materials, RTM processes and RTM design rules. This knowledge was transferred successfully to that industry. As a result, the first series production RTM components for the aerospace industry are now being manufactured in the Netherlands.

Lessons learned from the technology programmes carried out were:

- RTM simulations can be very useful when designing an RTM tool. However, in order to simulate the RTM process accurately, a good understanding of the RTM principle is absolutely necessary, since dominating details like race tracking must be built into the models.
- RTM process monitoring is essential for manufacturing thick components and to demonstrate reproducibility of the process
- The reproducibility of the quality of the preform will determine the robustness of the RTM process and will determine the scrap rate in series production
- The RTM mould makes or brakes the success of an RTM component.