# A DESIGN AND MANUFACTURING APPROACH TO REALIZATION OF PROTOTYPE OF A HELICOPTER TRANSMISSION COMPONENT BY COMPOSITE MATERIALS

S. Laurenzi, D. Di Nallo, M. Marchetti
Department of Aerospace and Astronautic Engineering, University of Rome "La Sapienza",
Rome, Italy.

E. Lalia Morra, E. Anamateros
Agusta-Westland S.p.A, Aerospace Composites Center,
Anagni, Italy

## Abstract

Helicopter transmission components are traditionally made of metal alloys. Advantages can be obtained by replacing the original configuration with composite materials using Resin Transfer Moulding (RTM) technology. The highest ratio of mechanical properties to density produces weight saving and reduction. Replacing metal with composites, requires structural analysis, appropriate tooling design combined with investigations of the material processability. This paper describes outlines studies performed and the results obtained to manufacture a helicopter transmission component by composite materials using RTM technology. The component is primary part with high structural, geometrical and operating complexity. The activities have been performed considering the same interfaces and lubrification system configuration of the original design as a fixed reference point. Due to this, a study of preform realization has been carried out and structural optimization design has been performed using braided composites qualified design allowable. The best results have been obtained using epoxy/carbon braided at 30 degrees angle to the longitudinal axis of mandrel and Carbon Fabric toughened system. In order to verify the reliability of the static design, a modal analysis has been performed. The modal results confirmed the validity of the static design. The optimised configuration of the composite transmission case weighs 23% less than the original cast metallic. Due to the impact on tooling design of resin flow development during the injection phase, processability behavior of 6K carbon braided has been analized. Tooling approach has been discussed and an example to optimize injection scheme has been reported.

## Introduction

Composite materials, compared to metals, offer superior fatigue properties, better corrosion resistance, considerable lower thermal expansion coefficient.

Developing of a new composite product requires a synergy among different disciplines and sometimes entities. A concurrent engineering approach among Agusta Westland, the University of Rome "La Sapienza" Department of Aerospace and Astronautic Engineering and ENAC (Italian Civil Aviation Authority) has been developed as shown in fig1.

**R**esin **T**ransfer **M**oulding process (RTM) is one of the most promising technology available today because of its capability to allow complex part manufacturing and components integration [2].

RTM is a closed mould process.

For a simple case, the lamination sequences is laying in a cavity, determining the thickness of the piece, between two closed half-mould and resin is injected by pressure. When the resin reaches the vent, the gate is clamped and the preform is impregnated. After cure, the closed mould is opened and the part removed [3].

This technology requires a strong design activity both for best preform methodology analysis and for mould and tools optimisation.

The preform realization is a critical aspect of the RTM technology because of its direct impact on the mechanical behavior of the cured laminate. The choice of preform technology is directly connected with geometrical complexity, fiber placement tolerances and resin flow behavior during impregnation.

Braiding has been chosen as preform technology to be used for the transmission component because of its conformability to conical shapes, high degree of automation that guarantee significant reproducibility and repeatability levels.

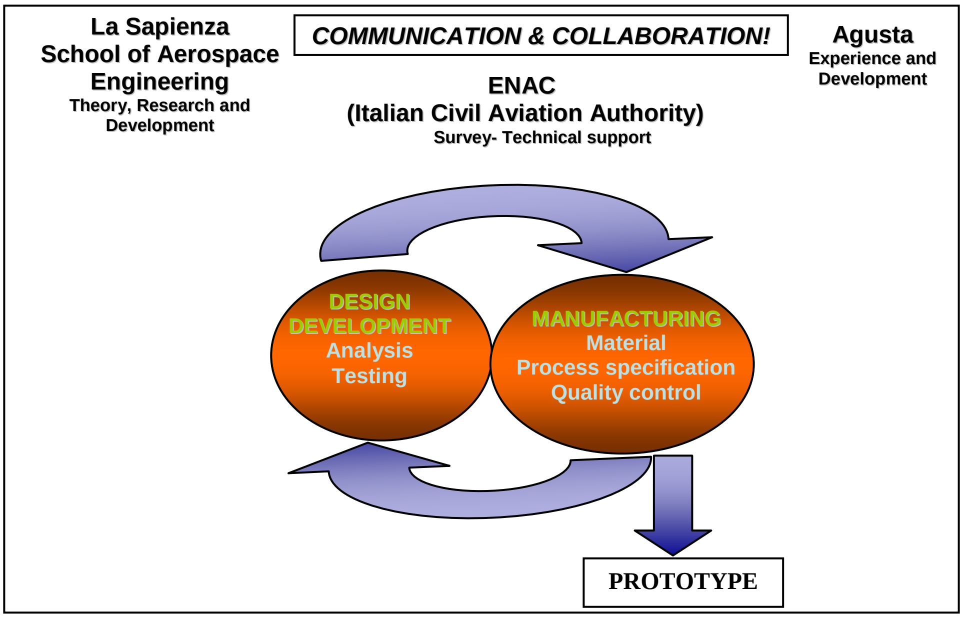


**Fig 1: share of activities**

## Structural Analysis

The aim of the structural analysis was to optimise the transmission component weight (objective function) and to preserve–improve the mechanical performances (project variables). For this purpose, a structural optimization design has been carried out for braided preform implementing an iterative procedure in MSC/Nastran finite element code.

### Structural optimization design

The numerical design performed is a constrained minimization problem [1]. The variation of the objective function (weight) occurs satisfying the structural constraints: the Tsai-Wu criterion, involving in plane induced stresses, and the maximum shear stress criterion that involves the out-plane stresses. ± 30°, ± 45°, and ± 60° fibers orientation have been investigated. The first step of the numerical work has been to realize a simplified model of the part. Since the weight of the braided preform changes with the braided angle, three starting model has been created with same weight of the corresponding metallic gearbox, considering an equivalent constant thickness along the profile. In each case the equivalent starting thickness has been determined by the following relations [1]:

$$Mtot = \rho comp(v1+v2) + Mstruts + Mst = 10.7 \text{ kg} \quad (1)$$

$$v1+v2 = \pi\, t\, [(r1+r2)a1 + (r2+r3)a2] - Sh\, t \quad (2)$$

$$t = (Mtot - Mstrut - Mst)/[\rho(\pi\, c - Sh)] \qquad \text{with } c = (r1+r2)a1 + (r2+r3)a2 \quad (3)$$

where the component transmission was considered as assembly of two cones corresponding to the two different slopes: “Mtot” is the metallic weight, ρcomp is the composite density, v1and v2 are the volume of the two section cones; “Mstruts” is the mass of the struts and “Mst” the mass of the stopper. r1, r2, r3, a1, a2, are respectively the radius of the first cone, the radius for the second cone and the corresponding apothems; “Sh” is the total surface of the hole and “t” is the thickness. The interfaces and geometrical constraints were preserved as well as the external surface and the diameter of the hole.
The steps of the work are shown in fig 2.

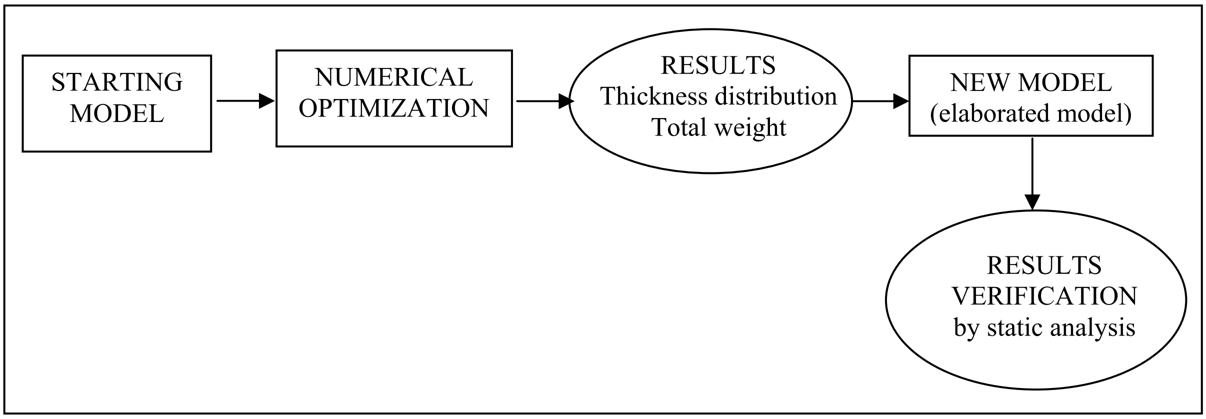


**Fig 2: scheme of structural procedure to determine the distribution thickness of the composite component transmission.**

**Model.** The following materials have been considered for analysis: Braided AS4 6K GP / 3M PR 520 for the conical shape, epoxy moulding compound XLD for the struts attachment areas.
Mechanical data were obtained from “Material Qualification Methodology for 2X2 Biaxially Braided RTM Comp. Material Systems” AGATE (NASA-INDUSTRY-FAA) report [6] and from Agusta S.p.a. specifications. The values were at room temperature dry 21.1 ± 5.5° C, in the above report.
A simplified finite element model has been adopted, with elimination of non-structural parts from the initial geometry. The elements were 2-D laminates with 4 nodes. Three rigid elements were necessary for applying load at 493 mm from the top surface of the cone and for maintaining the circular shape of the holes. In particular, two elements with radial arrangement have been adopted on the top and bottom bases. A vertical element, parallel to the axis of the cone (Z axis) with a length equal to 493 mm has been connected at the rigid element on top and with one node on the extremity for the application of the load.
The static limit load applied to the structure has been increased to a factor of 3 in order to simulate conditions at triple static limit load as established for the design composite critical structure and also to consider the high degree of uncertainty for aerospace part manufacturing. The applied load was represented with six components: three forces and three moments in the total coordinates system XYZ, where Z is the axis of the cone.
Due to the braiding technology limits to get in one shot a closed cone, a realization of two preforms and their joining has been conducted.
The simulation for the base has been performed with both carbon braided and Priform fabric materials.

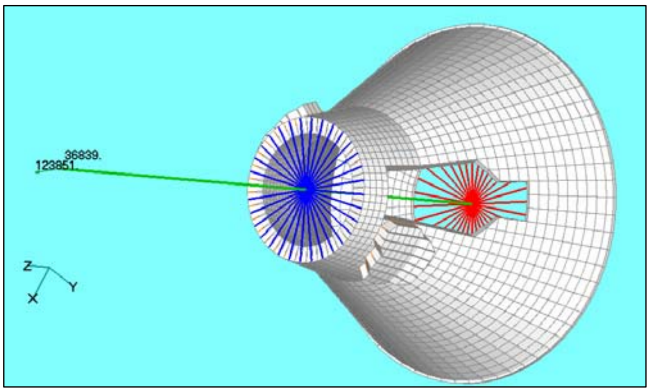

**Fig 3: simplified finite element model**

**Results.** Looking at table 1, considering carbon braided for both performs, the best configuration obtained is the ±30° braided angle, that corresponds to greater saving weight. In this case, the thickness varies between 21 mm-6 mm in the conical profile.
The ±30° braided angle configuration gives the first failure in plane. Figure 4 shows the trend of failure index supplied from the Tsai-Wu criterion: the more stressed zone corresponds to the struts attachment areas. The rest of the body presents an almost uniform and low value of failure index. The ± 45° braided angle configuration has a similar distribution of failure index to the previous case as shown in figure 5, but the first failure occurs by the maximum shear stress criterion.

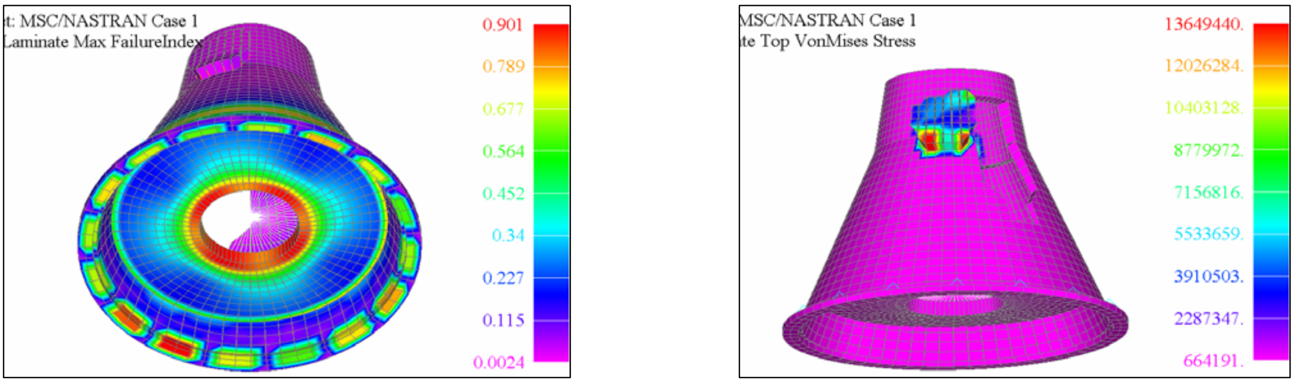


**Fig 4: static verification for braided laminates obtained with braided angle at 30°.**

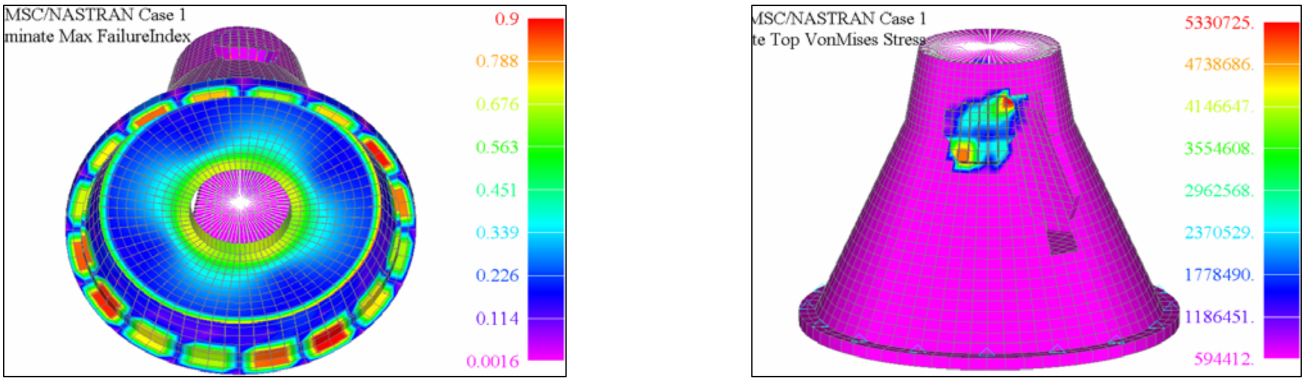


**Fig 5: static verification for braided laminates obtained with braided angle at 45°.**

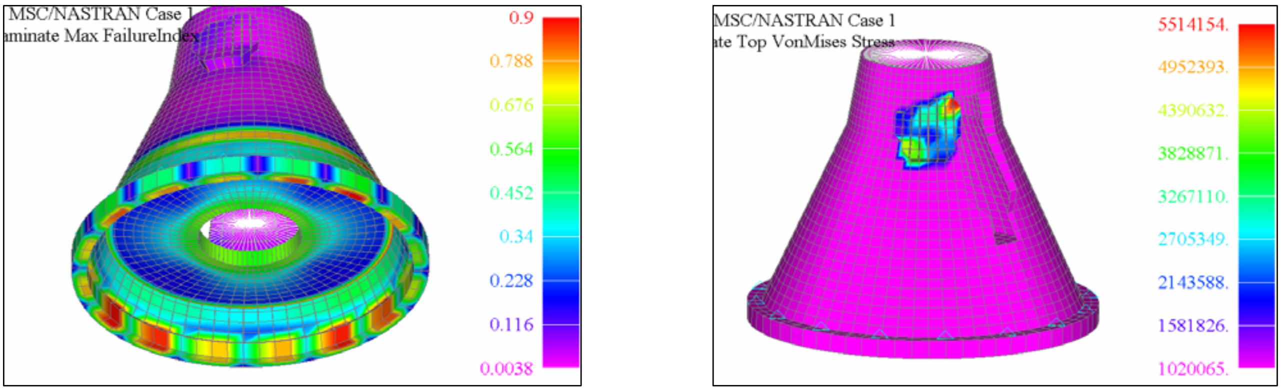


**Fig 6: static verification for braided laminates obtained with braided angle at 60°.**

| Braided angle | $V_f$ range cone shape and base | Weight optimized (Kg) | Max failure index | **ILSS** (braided) | Saving weight(%) |
|---|---|---|---|---|---|
| ± 30° | 0.58÷0.61 | 8.29 | 0.901 | 67.64 MPa | 22.5 % |
| ± 45° | 0.64÷0.65 | 8.87 | 0.9001 | 43.99 MPa | 17.1 % |
| ± 60° | 0.69÷0.71 | 9.34 | 0.9 | 23.99 MPa | 12.7 % |

**Table 1: Results obtained by structural optimization procedure considering braided perform for both preforms.**

| Braided angle | $V_f$ range cone shape | $V_f$ range base | Weight optimized (Kg) | Max failure index | **ILSS** (braided) | **ILSS** (fabric) | Saving weight % |
|---|---|---|---|---|---|---|---|
| ± 30° | 0.58÷0.61 | 0.6 | 8.19 | 0.894 | 67.64 MPa | 75MPa | 23% |
| ± 45° | 0.64÷0.65 | 0.6 | 8.28 | 0.9 | 43.99 MPa | 75MPa | 22.5 % |
| ± 60° | 0.69÷0.71 | 0.6 | 8.35 | 0.9 | 23.99 MPa | 75MPa | 22 % |

**Table 2: Results obtained by structural optimization procedure considering braided perform and Preform fabric.**

Table2 summarizes the results regarding the configuration with preform fabric base. This configuration, as we can see in tables1-2, gives us the best results at the same angles.

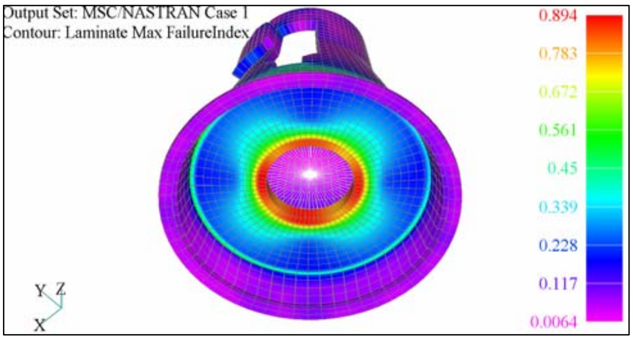


**Fig 7: in-plane failure index for carbon braided and Priform 977-20 RTM**

The figure 7 shows the failure index trend obtained from optimization design using carbon braided for the conic body and 977-2 RTM for the base. The 977-2 RTM is self-binding materials. This choice also satisfies the manufacturing point of view.

## Modal Analysis

Modal analysis has been performed to confirm the validity of the static design. If load frequencies are lower than resonance frequencies of the structure, it is shown that it is not necessary further dynamic design of the component. The first characteristic frequency of the optimized structure has to be greater than the maximum frequency of the applied load.
First five natural modes of vibration have been analyzed for each optimized configurations: ±30° braided, ±45° braided and ±60° braided. The auto-vectors have been normalized to unitary modal mass.
The first fundamental frequency of the external dynamic load considered:

$$f_1 = N*\Omega \qquad (4)$$

where N is the number of the blades of the helicopter and Ω (Hz) is the angular speed of the rotor.
We considered the first six harmonics with frequency equal to a multiple of $f_1$:

$$f_n = n*N*\Omega \qquad n = 1,2,...,6 \qquad (5)$$

Because of N = 4, e Ω = 260 r.p.m = 4.33 Hz, the range of applied load frequencies is among:

$$f_1 = 17,33 \text{ Hz} \quad \text{and} \quad f_6 = 104 \text{ Hz} \qquad (6)$$

In order to perform an accurate modal analysis, it is necessary to consider all the vibration modes between 0 Hz and the triple one of the maximum frequency of the external load (safety factor 3), that is 312 Hz. The figures 2-3-4 show that the preform at ±30° angle braided presents the first lowest characteristic frequency, about 534.43 Hz. This value is more than five times greater than last maximum frequency of the applied load. Therefore, static design is sufficient for the sizing component.

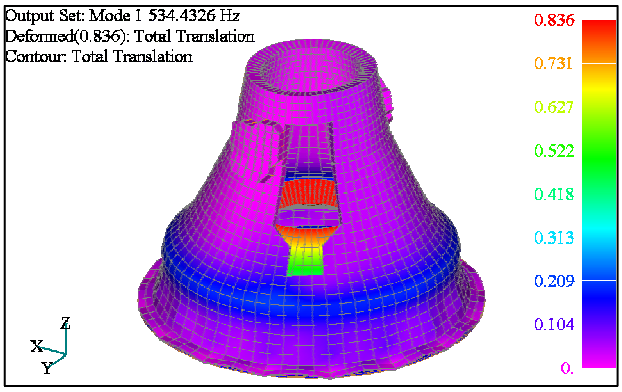


Fig 9: Modal analysis for 30° braided angle

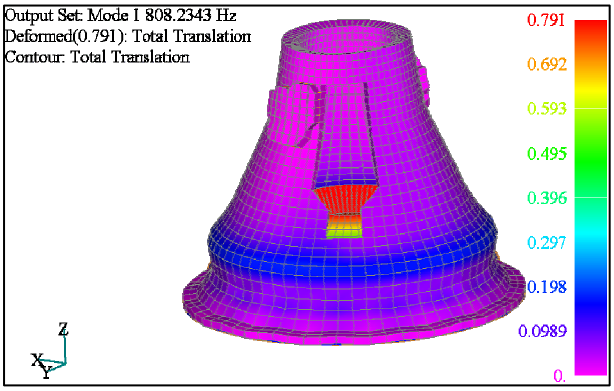


Fig 10: Modal analysis for 45° braided angle

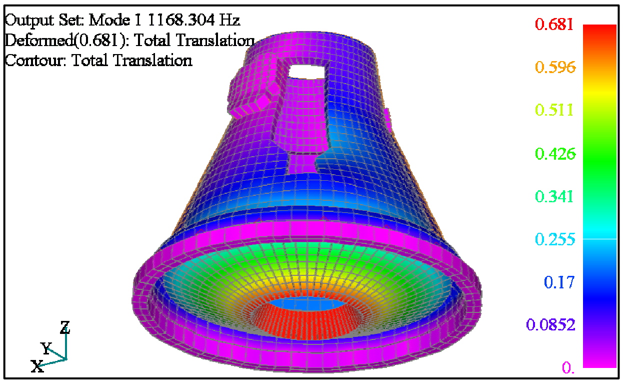


Fig 11: Modal analysis for 60° braided angle.

## Process: Flow Analysis

The structural design determines a conical preform having a thick profile to be impregnated. Therefore, study of the processability of thick braided preform is essential for the final choice of the fibers/resin and to approach the tooling design. A non-uniform impregnation of the fibers creates dry spots where there is no adhesion among the layers of the preform and creates a rough and discontinuous surface.
The behaviour of two BMI, three Epoxy resins and one benzoaxine resin have been observed to make a better choice of the matrix for the process.
The set of resins, to investigate, has been selected in order to withstand the maximum operational temperature as requested during normal flight activities and also during the applicable ultimate no oil condition.

## Processability

**Resins.** Realization of flat panels has been carried out to investigate the process ability of different resins with fixed type of braided carbon fibers preform. Experimental apparatus consisted on typical RTM system: mold, injection line, air compression, pressure vessel, oven. The mold has simple geometry with single point of injection and vent placed in opposite to the top half-mold. Different frames allow thickness adjustment. In order to get a linear injection, preform has been situated at 2cm in ahead respect to the point of injection. The apparatus is shown in Fig 13. The specimens had thefollowing features:
fiber volume fraction = 0.67
angle of braided = ±45°
length edge = 200mm
thickness = 2.4 mm
number of layers = 5
The basic parameters involved in resin selection for RTM system are both injection and cure temperature and the relation between them and the viscosity profile. Also filling time, handling and visual analysis of the cured piece has been taken in account.

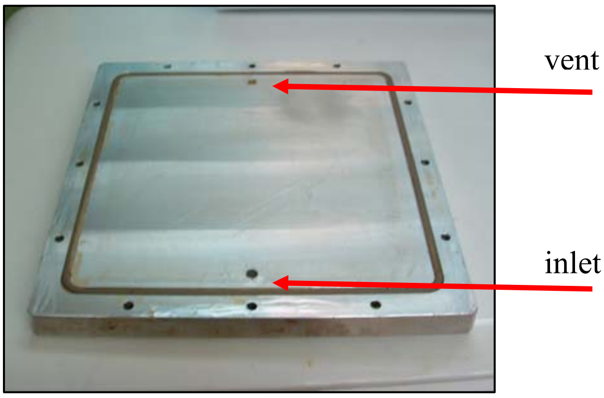


**Fig12: half-mold used for process ability test.**

Handling evaluation of resin systems has been carried out considering the response of increasing rate viscosity reducing the operative temperature of 10°C. The tested resin and the values of process parameters for running test are shown below in table3. Table 4 summarizes the results.
In the group of bismaleimide systems, the resin that has shown more sensitive response is the CYCOM 5250-4 RTM. A similar behaviour has been observed for RTM 651 in small scale. In the group of epoxy systems, the most friendly resin appears to be the RTM 6.
RTM6 while having shown good handling properties, it has been found not suitable for the component transmission thermal-chemical requirements. Therefore, the selection campaign could drive to consider RTM 651 for BMI group and LX 70303.0 as candidates for further investigations.

| **Type** | **resin commercial name** | **Degas** | **T Mold (°C)** | **T Injection (°C)** | **Initial viscosity (mPa s)** | **Gel Time** | **Cure** |
|---|---|---|---|---|---|---|---|
| EPOXY | CYCOM 890 | 30min @ 95°C vacuum | 80° | 80° | 250 | 50 min @ 180°C | 2h @ 180°C |
| EPOXY | CYCOM 977-20 RTM | 45min @ 95°C vacuum | 75° | 90° | 200 | - | 3h @177°C |
| EPOXY | RTM 6 | 10 min @ 80°C vacuum | 120° | 120° 60° | 500 | >240min @ 120°C | 75 min @160°C |
| BMI | RTM 651 | - | 156° | 156° | 150 | 62min @ 160°C | 4h @190°C |
| BMI | CYCOM 5250-4 RTM | - | 156° | 93° | 500-600 | 35min @ 177°C | 4-6h @ 190°C |
| BENZOAXINE | LX 70303.0 | 30 min @ 50°C vacuum | 80° | 110° | 50-100 | 22 min @ 177°C | 3h @ 180°C |

**Table3: resins and parameters used for process-ability test**.

| Resin | Injection Time | Rate of viscosity |
|---|---|---|
| CYCOM 890 | 2’. 21’’ | medium |
| CYCOM 977-2 RTM | 2’.50’’ | low |
| RTM 6 | 3’. 06’’ | low |
| RTM 651 | 1’. 08’’ | medium |
| CYCOM 5250-4 RTM | 4’. 34’’ | high |
| LX70303.0 | 3’. 00’’ | low |

Table 4: results of process-ability test

**Permeability.** In order to evaluate the resin flow behaviour in the braided preforms, several experiments have been conducted.
A rectangular thick glass RTM mold has been used to observe the progress of the flow front visually. The thickness of the mold has been adjusted by using different frames. A grid had been drawn on the top and bottom glass to measure the fluid flow front position.
The greatest challenge for flat specimens manufacturing is the attainment and the maintenance of a determined braided angle. For this purpose, according to the methods described in AGATE report (6), some cylindrical PVC mandrels has been used with fixed diameters, in order to obtain the desired angle. The braided sleeve is put on the mandrel and the fibers are fixed with some tape along the edges. The cut layers are then plied together.
As demonstrated in previous work [1], no process defects like fiber-washing and racetraking have been observed for 6K braided carbon fibers preform.

**Fig 13: experimental running.**

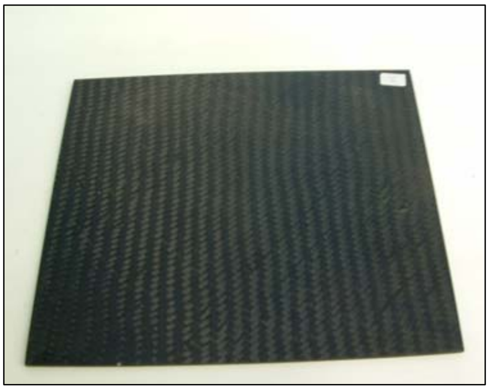

**Fig 14: 6K carbon braided RTM 651panels.**

The injection pressure used for 6K carbon braided has been changed to 0.5 atm-4 atm with a fiber volume fraction between 50%-65%.
Panels with 12K carbon braided have required a restrict range of both injection pressure and fibers volume fraction due to fiber washing. Fiber volume fraction equal to 50%, has been positive processed using just vacuum. A maximum of 1 atm could be reached with fiber volume fraction equal to 67%. For each tow size pressure/ volume fraction relations are going to be analysed.

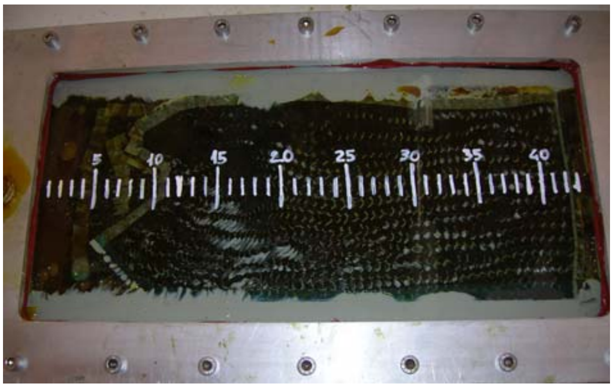


**Fig 15: 12K carbon braided fiber- washing obtained for pressure=1atm and fiber volume fraction=50%.**

Fixing fiber volume fraction at 0.67 also weight/orientation correlation has been investigated. Flat preforms at 30°, 45°, 60° braided angle have been manufactured. Three types of 6K T300 carbon braided reinforcements have been used. The fiber volume fraction of the flat braided samples has been determined by the following well known formula (7), considering that changing the braided angle the samples assumes a different weight per unit area

$$V_f = \frac{nA}{h\rho} \tag{7}$$

where h is the thickness of the frame (8mm, 11mm, 15mm), ρ is the average density of material (1,7 g/m³), n is the number of layers varying to keep constant the fiber volume fraction for several h, A is the weigh for unit area.
The table5 reports the weight of carbon braided layers used for the experimental tests.

| *α* | *144/05* | | *144/06* | | *120/05* | |
|---|---|---|---|---|---|---|
| ***30°*** | *49mm* | *428g/m^2* | *88mm* | *479g/m^2* | *64mm* | *554g/m^2* |
| ***45°*** | *70mm* | *370g/m^2* | *125mm* | *415g/m^2* | *90mm* | *480g/m^2* |
| ***60°*** | *86mm* | *428g/m^2* | *153mm* | *479g/m^2* | *110mm* | *554g/m^2* |

**Table 5: results of process-ability test**

The 1-D version Darcy's law to determine de permeability parallel to the mandrel axis was adopted:

$$K_x = \frac{\mu \Phi slope\,of\left[x^2{}_f(t_f)\right]}{2\Delta P} \tag{8}$$

where μ is the viscosity of resin, Φ is the porosity of the perform, ΔP is the pressure gradient, $X_f$ is the flow front position at $t_f$ instant.

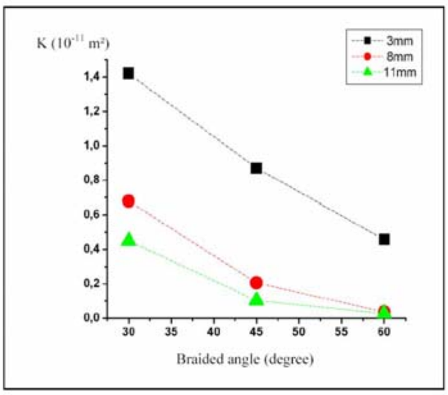


**Fig 16: permeability for carbon braided 144-05.**

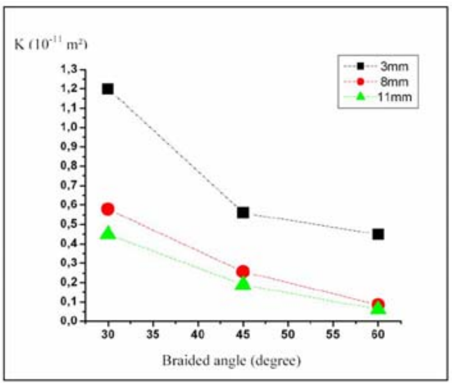


**Fig 17: permeability carbon braided 144-06.**

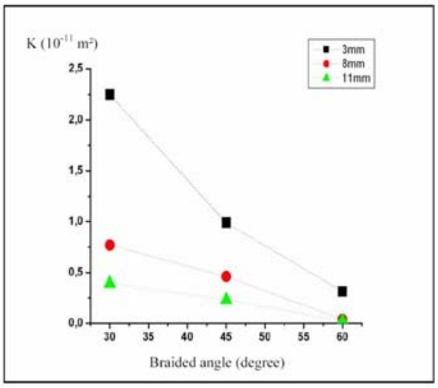


**Fig 18: permeability carbon braided 120-05.**

The results show that, for all materials, the permeability decreases with increasing braided angle due to an additional resistance generated by tow misalignment from resin flow direction. For all materials, the permeability parallel to the mandrel axis at 60° decreases notably, which results in a considerable increase of the time of impregnation.

## Manufacturing Approach

Every composite component requires more tooling design than metallic counterpart, especially in case of complex shape. Transmission component is supposed to be integrated as much as possible to take all advantages from the RTM process. In order to do that, different scenarios have been carried out. In any case, the oil filler, oil connector and oil tank have been considered being connected by a secondary bonding.

### Preform technology

A braiding tooling approach has been considered because of the braiding high torsional stability and conformability to conical shape. Furthermore, braiding allows components integration reducing manufacturing cost.
Carbon fibers are braided on a mandrel in order to obtain a stiffened structure.

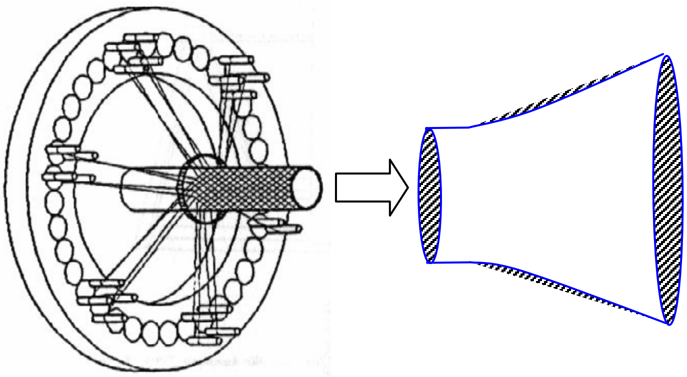

**Fig 19: braiding preform process.**

The base is realized as a separate component made by preformed fabric material and then connected to the braided perform after several fiber layers deposition. Main Rotor Servo Actuators and MGB Struts Attachment areas can be fit on the conical preform during the braiding process after an opportune number of layers. Struts attachment inserts have been dimensioned in order to preserve the local inclination of the plate and to maintain the dimensions and the positions of the holes to guarantee the interfaces.
The base of the insert has been designed to maintain the original inclination and the curvature of the conic body in order to facilitate the arrangement and the continuous contact with the underlying fibers. This will allow to distribute uniformly the stresses to the perform avoiding local concentrations. Preliminary insert geometry is shown in figure 20.

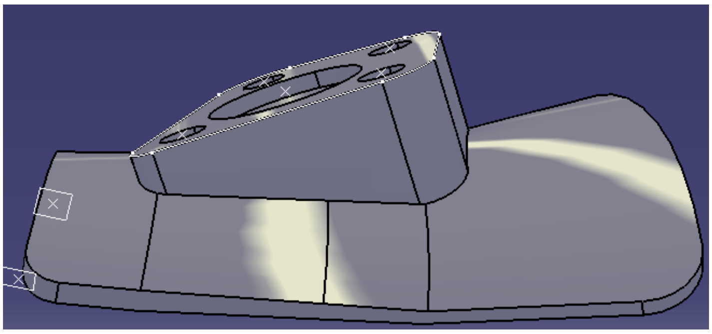

**Fig 20: final geometry of the insert.**

The final dimensions of inserts, as thickness and length, must be refined according to the loads agents on the component. For these purposes, an optimization for design sensitivity is currently under development procedure. The inserts have been considered made by epoxy moulding compound in the structural optimization design. Using design sensitivity, it's also possible investigate different materials for the attachment areas in order to find a best configuration as function weight-dimensions.
Mandrels can be realized in different ways, but it must be removable and permit insertion the different element. For example, it can be built by low melting temperature material or water soluble material to permit the part removal. The ceramic soluble has been taken in account. It is easy to use because it's fluid to room temperature, it solidifies at thermal cycle, about 120°C and melts in hot water. As shown from several test that have been performed, the disadvantages of a ceramic mandrel are the necessity of a mould, the particular attention for part mixed and environment condition, the brittle behaviour. For these reasons, the final choice to manufacture a prototype, creating a mandrel obtained jointing fastened parts as shown in the following fig 14. In this case, the challenge is design an easy-handling mandrel.
The external mould should be divided in removable parts recognizing critical areas for tool taking out.

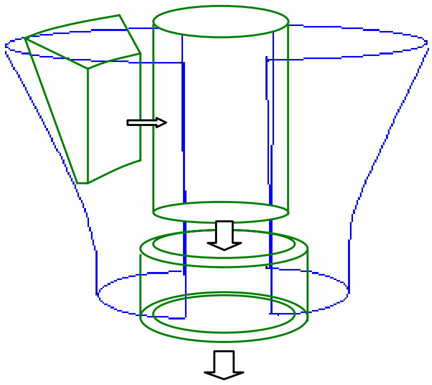

**Fig 18: scheme of tool assembly**

Using this mold, surface finishing will be very high and dimensional tolerances very close. Component strongly integrated.

## Injection Scheme

A dedicated tooling design analysis has been performed in order to guarantee the completion of wetting process of the preform: the more complex the shape and the arrangement of the fibers the more difficult the impregnation. For these reasons, the determination of the optimal position of the injection gates and the vent points for the mould is required. Experiments have been performed to evaluate the permeability of the preform. Knowledge of the permeability is important because it determines the flow patterns inside the preform and the filling time of the mould as well. The filling time has to be compatible with the resin pot life to guarantee the homogeneous wetting of the preform. Starting from the permeability data, a numerical simulation of the injection phase has been used to assess the filling time for the real piece. The simulation process allows to reduce the cost-time of design tool. Different positions affect greatly the filling time and the quality of the finished part. Several different injection schemes have been considered in order to choose the best compromise between requirements of filling time and mould design.
The permeability values used in the simulation have been reported in previous work [1].

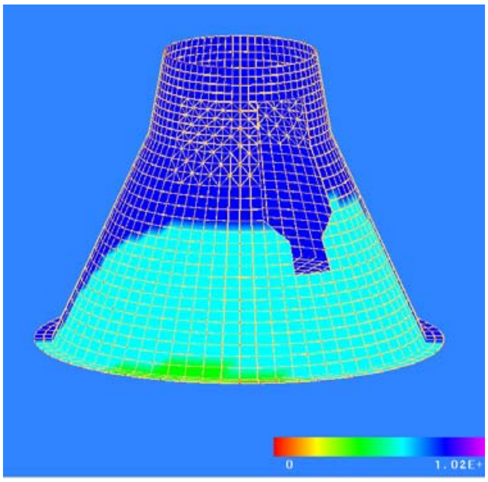

**Fig 21: pressure gradient inside the preform during impregnation.**

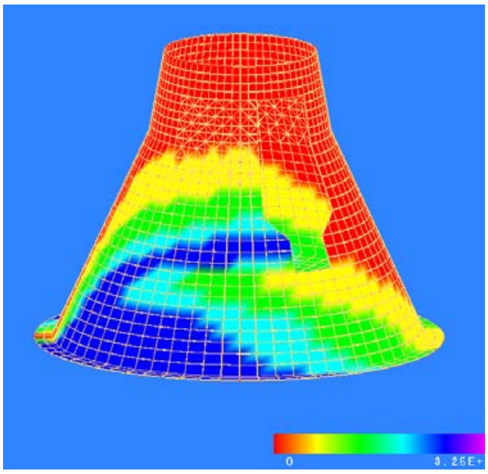

**Fig 22: filling time inside the preform**

In the scheme reported the injection points have been placed on the top border of the conic shape and the venting points on the base. As can be seen in Fig 22 the total filling time with this configuration is about 30 minutes comparable with the resin pot life limit.

## Conclusion

Designing a complex composite transmission component requires a synergy among the structural engineer and the process engineer to satisfy structural requisites with manufacturing aspects. The study of the resin flows, parallel to that structural is necessary for an opportune choice of materials and tool design. The upper developing activities have been performed in order to guarantee high quality and cost-effective resin transfer molding (RTM) manufacturing within the aerospace standards as requested by the airworthiness regulations. Composite configuration was reached through out a detailed design study that it led to an optimized composite laminate thickness and fibers angle lay-up. The best results have been obtained for sequences of braided laminates with braided angle at 30° respect to axis of mandrel. Results have shown the composite top case could drive to a weight saving of 23% compared to the original cast metallic configuration. Anyway the final design configuration will be defined after that a careful and detailed fatigue analysis will be completed.
A manufacturing approach for prototype of helicopter transmission component has been set-up, together with an idea of its respective tooling based on permeability analysis.

## References

1. S. Laurenzi, D. Di Nallo, F. Valente, M. Marchetti, E. Lalia Morra, E. Anamateros "Re-design of a helicopter component transmission by composite material", Proceedings of 45 st Israel Annual Conference on Aerospace Sciences, February, 2005.
[2] T. Kruckenberg et R. Paton, "Resin Transfer Moulding for Aerospace Structure", Kluwer Academic Publisherws1998.
[3] M. Marchetti, D. Cutolo, Tecnologie dei materiali composite, Esa, 1991.
[4] S. P. Peters, Handbook of Composites, second edition 1998 Chapman & Hall, London UK.
[5]S.G. Advani and E.M. Sozer, "Process Modeling in Composite Manufacturing", Marcel Dekker, Inc. New York-Basel.
[6] Material Qualification Methodology for 2X2 Biaxially Braided RTM Comp. Material Systems" AGATE (NASA-INDUSTRY-FAA) report.