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ORIGINAL ARTICLE

Composite part design based on numerical simulation of the manufacturing process

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Abstract In aeronautics, the decreased density of structural components is a major factor to consider in order to satisfy economic, environmental, and technical requirements. Using composite materials is justifying good weight to mechanical strength compromise. Mechanical strength depends on shapes, dimensions, and materials defined at the design stage and in manufacturing and assembling process of the part. In this article, a general method is proposed to evaluate the performance of the design choices based on the failure risk of an assembled part. This evaluation integrates manufacturing deviations from the shaping operation (resin transfer molding). Three criteria are derived from numerical simulations of RTM process and assembly phase. These criteria assist the designer early in the design cycle to appreciate the consequences of manufacturing choices on the mechanical strength of an assembled part. The approach will be applied to an airplane component.

Keywords Resin transfer molding (RTM) · Numerical simulations · Failure risk · Design for manufacturing and assembly (DFMA)

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1 Introduction

The key challenges of the aeronautical industry today are fuel saving, safety specifications in flight, and environmental protection. The current strategy used to meet these challenges consists of minimizing aircraft density while guaranteeing its mechanical behavior: that leads to drastic optimization of all constituent parts [1]. For this reason, composite materials are more and more used in preference to aluminum alloys. For these materials, reduction of mass requires to take into account the impact of industrialization (like warpage). Usually, there are several design and industrialization alternatives that lead to a solution respecting the technical specifications. The choice among these feasible solutions is mainly based on knowledge of the strength of the part and the optimization of its shapes.

The challenge is to find the best weight/strength by combining:

- Structural parameters (choice of composite components, number of plies forming the preform...)
- Industrialization parameters (tool configuration, characteristics of resin transfer molding (RTM) cycles, etc.).

The choice of structural parameters is included in the design process. This is not the case for industrialization parameters which are often defined later although they have a major influence on the behavior of the part and could induce uncertainty on mechanical properties. These uncertainties are generally compensated by the introduction of safety factors which lead to increase the volume of parts and therefore their masses.

To minimize the mass, it is necessary to quantify the coupling impact on one hand of structural parameters and on the other hand of industrialization parameters on the mechanical behavior of the part earlier in the design cycle.

This quantification is essentially based on comparisons of characteristics between the nominal part (from CAD model) and the real part (injected).

In this article, it is proposed to introduce a new approach for considering at the earlier design phases both the design and manufacturing constraints coming from RTM process and from the functional requirements of the injected part. To do so, two types of deviations are defined: geometrical deviations and volumetric impregnation deviations of RTM shaping. These different sources of manufacturing deviations will have a direct influence on the mechanical behavior of the assembled part. Usually, geometrical deviations can be compensated by contact with the adjacent parts during the assembly phase [2]. This compensation will generate an important state of heterogeneous residual stresses in the part [3]. Moreover, the volumetric impregnation deviations tend to decrease the mechanical performance of the composite material. These cumulative phenomena could lead to failure of the part even if, separately studied, all of them remain under safety levels. To consider it, a coupling analysis between these two sources is introduced through a failure risk index to guide the engineer in these design and industrialization choices. Initially, it is proposed a literature statement which allows identifying the key parameters inducing manufacturing deviations related to the injection and cooling phase. In a second step, a methodology is defined for estimating the failure risk due to the different sources of manufacturing deviations. The introduction of three criteria is set up to measure the performance of alternative design solutions and industrialization. The coupling consideration between them and the exploitation of the results allow to define a new design for manufacture and assembly approach. This work is applied in a particular aeronautic part.

2 Classical approach for part designing

The design of composite parts has to consider structural parameters. Thus, the designer determines the structural characteristics of the piece to ensure its resistance to the stresses defined by the functional requirements (Fig. 1, part design). In a second step, during the industrialization definitions, the engineer adapts a few design parameters and defines the industrialization parameters in the aim to manufacture the part (Fig. 1, mold design).

This sequential design process leads to expensive and no optimal solutions. Furthermore, with the RTM process, the mechanical properties are strongly dependent of the industrialization phase. For example, the appearance of air bubbles is mainly related to the position of gates and vents which is defined at the tool design stage.

Manufacturing deviations are quantified only after the manufacture of parts (Fig. 1, part manufacturing), and their effects appear in the assembly phase (Fig. 1, part assembly). To reduce the needed time in the design phase, it is possible to set up numerical simulations of injection and cooling phases and then the assembly phase. These simulations allow predicting the impact of manufacturing variability on the mechanical behavior of the part and thus limiting the test phases.

According to the previous paragraphs, a classification of manufacturing deviations of RTM process is proposed and follows these two families:

- Geometrical deviations
- Volumetric impregnation deviations

The first source of variation in the geometrical characteristics (warpage) is mainly due to the laminated preform architecture and the physical phenomena inherent in the crosslinking of the resin [4]. The sources that lead to geometrical deviations are analyzed in several scientific articles. The purpose of this research is to act on the sources to reduce the manufacturing variability. Authors propose in [5] a mathematical model to understand the structural distortions in the case of T shape profile. Others [6] propose to use a particular linear model base on finite elements method to identify and quantify the factors contributing to spring in. In [7], the parameters that lead to “spring in” and the “warpage” for parts realized with autoclave are identified.

The second source of deviations corresponds to the volumetric impregnation deviations. They are essentially due to poor impregnation of the preform, which results in dry areas or residual porosity.

Many scientific researches are aimed at reducing volumetric impregnation deviations, they are based on optimizing the design tools [8–10] or on methods of controlling flow and pressure of resin [11]. Volumetric impregnation deviations lead to changes in the mechanical properties of the material resulting from the impregnation operation.

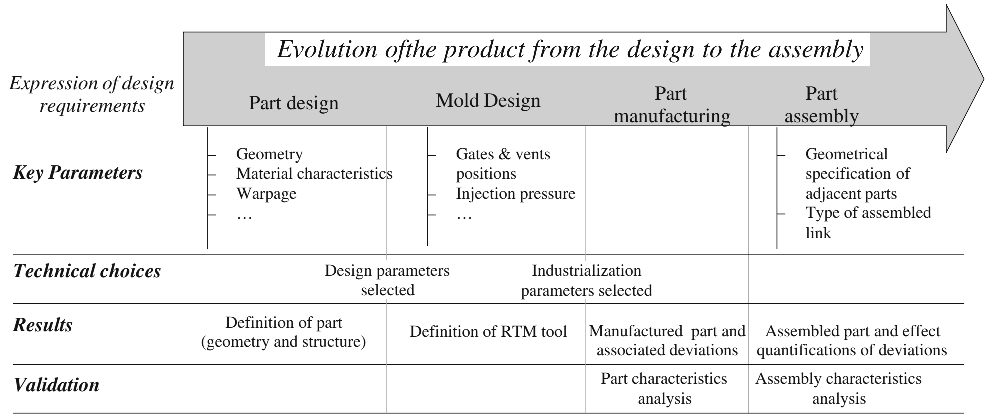
According to various studies listed, it is crucial to develop a methodology to integrate both the functional requirement constraints but also the industrialization constraints and their effects on the behavior of the part.

The various works listed are intended to identify causes of manufacturing deviations and try to reduce them. In this article, the main goal of the developed approach does not consist in controlling or reducing manufacturing deviations but to estimate their impact on the mechanical part assembly earlier in the design cycle.

3 Methodology

Engineers use software tools based on finite element during the preliminary phases of composite part design that allows to quantify the impact of geometrical deviations related to

Fig. 1 Design and industrialization phases of manufactured part



the cooling phase and, for RTM process, to visualize the evolution of the resin flow into the preform. Although these tools are available, most of the time their uses are exclusively reserved to a few specialists. Moreover, these simulations are performed with different actors from design or manufacturing services and for different stages of the part life cycle. The communication between these actors and services of the company is often non-existent and some choices will induce specific solutions in the industrialization phase.

For guiding engineers in selecting solutions, the performance estimation of design and industrialization choices are quantified by numerical simulations. The methodology developed could be considered as a design for manufacturing approach. It is based on the quantification of manufacturing deviations obtained from numerical simulations of phases of cooling and RTM injection. Then, the estimation of failure risk of the assembled part could be calculated.

Initially, for the RTM cycle, the injection duration of the resin and geometrical deviations are computed. From the geometrical deviations and constraints due to assembly process, the failure level of the part is estimated. This risk of failure is based on a failure criterion of composite materials (e.g., Hashin criterion). The injection time is post-processed to quantify the volumetric impregnation deviations. It is then possible to locate areas of the part with a risk of bad impregnation.

To take into account the coupling manufacturing variability on the mechanical behavior of the part, it is proposed to stack the failure risk to the risk of volumetric impregnation deviations. Then, to consider coupling phenomena, a phenomenological failure criterion is used, and its value is majored in function of the volumetric impregnation deviations. The final level of the failure risk is used to measure the performance of the solution and provides relevant information for a selection of structural and industrialization parameters. This information helps engineers in the selection of solution alternatives. The proposed approach is illustrated in Fig. 2.

4 Industrialization performance

To guide engineers in selecting the best configuration among the feasible alternatives, three performance criteria are introduced. They are based on simulations of cooling, of resin flow in the preform, and of assembly as shown in Fig. 2. Two criteria are used to estimate the performance of the RTM injection phase by identifying the risk of volumetric impregnation deviations. Relations set up to calculate the level of criterions are based on two assumptions coming from the literature:

– The distance between the area during the impregnation and the injection gate is a key parameter to ensure good impregnation of the preform [9].
– The filling time of the preform must be low to ensure good filling [12].

The third criterion defines the performance phase of cooling. The performance is obtained by quantifying the state of residual mechanical stresses after the assembly phase (Hashin criterion) from the geometrical deviations of cooling phase. In the performance analysis, this failure criterion is a priority because it guarantees the integrity of the part and must remain below a threshold value. The analysis of two other criteria completes the estimation of the performance of the manufacturing phase. The exploitation of all criterion values and their distribution along the part allows a global estimation of the performance. The following paragraphs describe every criterion in more details.

4.1 Performance criterion 1: RTM mold (Cr_1)

The aim of the Cr_1 criterion is to detect faults in the filling of the constituting elements of the meshed part. This analysis is based on the ratio between the time lapse from the start of filling each element and its distance to the closest injection gate. This criterion is used to determine if the element is close to a gate and is filled late; it is probable that the flow of resin into the preform is not occurring in the best conditions. This problem may be a cause of the

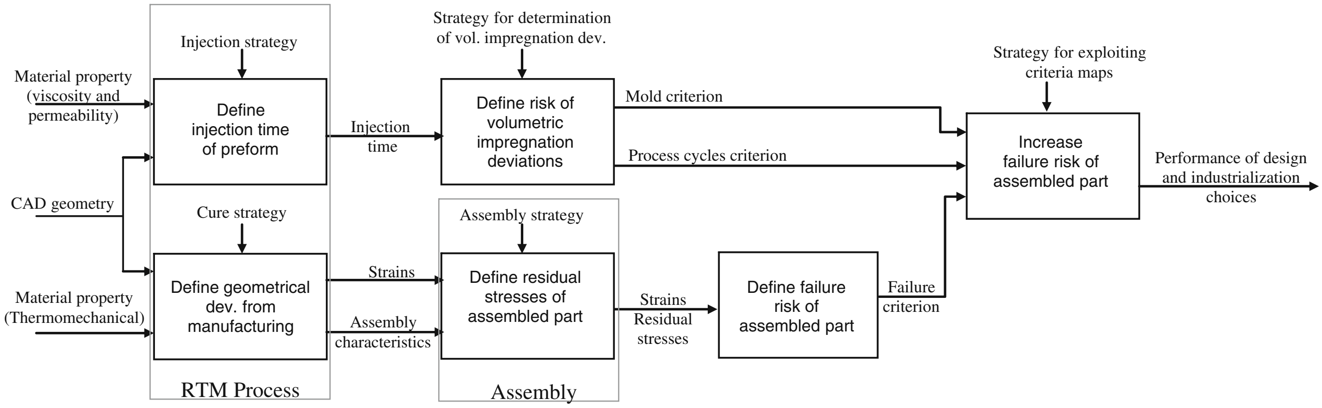


Fig. 2 Approach developed to estimate failure of manufactured part

appearance of deviations of mechanical properties. The Cr_1 criterion is calculated through Eq. 1.

$$Cr_{1i} = \frac{tsf_i}{d_i}$$
and
$$d_i = \min(||P_i, Pg_j||) \quad (1)$$
Such as $i \in$ N and $i \leq n$
$j \in \{1, 2, 3, 4, 5\}$

where Cr_1=[Cr_{11}, Cr_{12}, … Cr_{1n}]

tsf_i Is the time to start filling the element i
P_i Corresponds to the list of centroid coordinates for every elements i
Pg_j Corresponds to the list of the coordinates of the j gates
n The number of elements of the meshed part.

4.2 Performance criterion 2: RTM cycle (Cr_2)

The Cr_2 criterion analyzes the way in which the elements are filled. The aim is to detect elements of the meshing that are filled in several stages or over a long time. These discontinuities during the filling phase may be responsible for the appearance of air bubbles and hence deviations of mechanical properties when the resin is completely cross-linked. Criterion Cr_2 can also be used to detect zones in the preform that will never be completely filled with resin. This criterion corresponds to the time to fill an element [13]. This criterion is given in Eq. 1.

$$Cr_{2i} = tff_i - tsf_i, i \in \mathrm{N\,and\,i} \leq \mathrm{n} \quad (2)$$

where Cr_2=[Cr_{21}, Cr_{22}, … Cr_{2n}]

tff_i Is the time to finish the filling of the element i
tsf_i Is the time to start filling of the element i
n The number of elements of the meshed part

Figure 3 summarizes the calculation of the Cr_1 and Cr_2 criteria based on the resin flow during the injection phase. It is illustrated for the criterion calculation of the element (Elt_i).

4.3 Performance criterion 3: assembly (Hashin) (Cr_3)

The Hashin criterion is a phenomenological criterion. It introduces the degradation mechanisms of the material. It was first presented by Hashin [14] in 1980. This criterion is applied to unidirectional composites and identifies four modes of material failure. These four modes concern the rupture either of the fiber or of the resin under traction or compression. These different failure modes are represented by inequations 3, 4, 5, and 6. Failure has occurred if one of the four inequations is not respected. The Samcef® software proposes different ways of calculating this criterion [15]. The direction 1 designates the axis of the fibers. For all equations from 3 to 7, it is supposed that $i \in N$ and $i \leq n$, then the criterion is defined through four failure criterions as written below:

– Failure of the fibers,

$$hs^1{}_i = \frac{\sigma_{1i}{}^2}{X_t{}^2} + \frac{\tau_{12i}{}^2 + \tau_{13i}{}^2}{R^2} \leq 1 \quad (3)$$

R Is the shear strength, identical value in planes 1, 2 and 1, 3
X_t Corresponds to the ultimate tensile strength

– Failure of the fibers under compression

$$hs^2{}_i = \frac{\sigma_{1i}{}^2}{X_c{}^2} \leq 1 \quad (4)$$

X_c Corresponds to the ultimate compressive strength

– Failure of the matrix under traction

$$hs^3{}_i = \frac{(\sigma_{2i} + \sigma_{3_i})^2}{Y_t{}^2} + \frac{\tau_{23_i}{}^2 - \sigma_{2_i}\sigma_{3_i}}{S^2} + \frac{\tau_{12_i}{}^2 + \tau_{13_i}{}^2}{R^2} \leq 1 \quad (5)$$

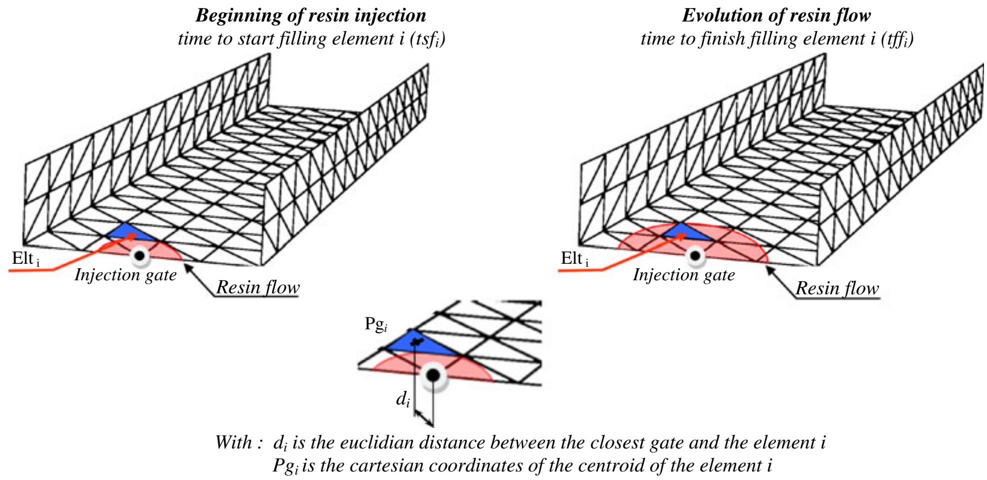


Fig. 3 Illustration of the calculation of Cr_1 and Cr_2 in function of injection time

S Is the shear strength in plane 2, 3 and Y_t is the ultimate traction strength

– Failure of the matrix under compression

$$\mathrm{hs}^4{}_i = \frac{1}{Y_c}\left[\frac{(Y_c)^2}{2S} - 1\right](\sigma_{2_i} + \sigma_{3i}) + \frac{(\sigma_{2i} + \sigma_{3i})^2}{4S^2} + \frac{\tau_{23i}{}^2 - \sigma_{2i}\sigma_{3_i}}{S^2} + \frac{\tau_{12i}{}^2 + \tau_{13i}{}^2}{R^2} \leq 1 \tag{6}$$

Y_c Is the ultimate compressive strength

In this study, as the main concern is to determine the risk of failure, it is proposed to calculate, for every element of the meshed part, the maximal level of the four Hashin scenarios as shown in Eq. 7.

$$\mathrm{Cr}_{3i} = \max(\mathrm{hs}^1{}_i, \mathrm{hs}^2{}_i, \mathrm{hs}^3{}_i, \mathrm{hs}^4{}_i) \tag{7}$$

4.4 Associated analysis

Every performance criterion is calculated for every element of the simulated part. The aim is to identify both mapping values by criterion type and a histogram of their distribution. Based on these two graphs, it is possible to link the criterion level to the position in the part. It is proposed to identify the outlier values of criteria by the mean of histogram. These plots allow to easily highlight the outliers.

These areas of extreme values (outliers) represent areas with loose of performance (risk of volumetric impregnation deviations) and a high levels of residual stress. The main advantage of these two types of representation is that the identification of areas combining risk of lost performance is facilitated. The implementation of the methodology is detailed in the following paragraphs on a structural part of an aircraft.

5 Background

5.1 Structural and functional description of the part

The approach of defining the performance of a technical solution is applied to an aircraft part: a spar. The spar is often the main structural member of the wing. This technical component carries all the loads of the wing which are mainly bending solicitations. Spars are also used in other aircraft aerofoil surfaces such as the tail unit or fin and are used for a similar function. The studied spar is a center spar of the horizontal tail unit of an aircraft which is composed of three spars (in rear, central, and front positions) (see Fig. 4).

The geometry of this part is a uniform U-shape cross section. The design procedure and the aeronautic certification determined that a multiaxial stiffener should be used to manufacture the preform. The multiaxial stiffener is a non-crimp fabric [90/45/-45] of unidirectional layers stitched in place. The resulting lay-up is a preform with no fibers in longitudinal direction. To optimize the mass density of the spar, the preform is made up of four zones of different thicknesses (Fig. 5), with the thickest zone (zone 1) located where the spar is clamped onto the central part of the tail unit, and the thinnest zone (zone 4) at the opposite end. The thicknesses, lengths and laminated preform architecture are given in Table 1.

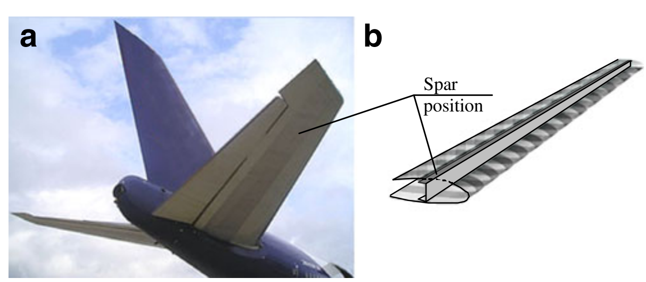


Fig. 4 Illustration of the studied part. **a** Horizontal tail plane on the aircraft. **b** Detail of the spar position

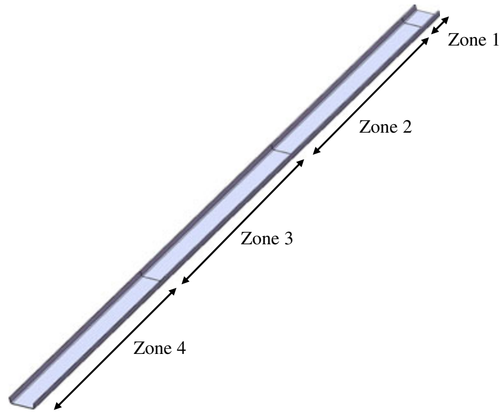


Fig. 5 Description of spar zones

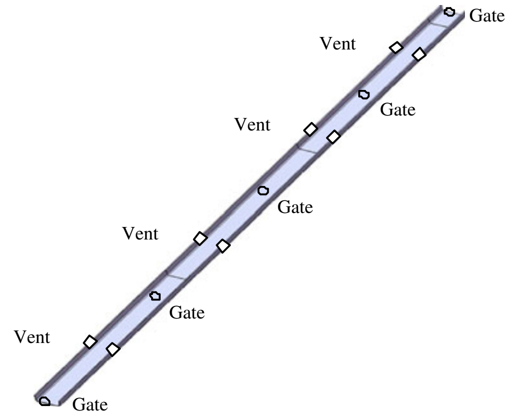


Fig. 6 Position of gates and vents

5.2 Manufacturing process

The spar is manufactured by RTM and the preform is produced by manual lay-up. When designing zone by zone, there needs to be a good organization of the stiffener panels (cutting, storing, and stacking) to ensure the conformity of the lay-up. Different checks were done to guarantee the quality of the component. The most frequently used were:

– Visual inspections to detect any lack of resin on the surface (dry spot)
– Ultrasonic inspections to detect residual porosity inside the part after the injection phase

These local verifications of the conformity of the injected part are not sufficient. Indeed, during the assembly phase, the initial deviation due to the strategy of the optimization of the mass, lead to design a material with anisotropic behavior that is responsible to geometrical deviations appearing in the cooling phase of the RTM process. These deviations have to be compensated by the assembly process and overconstrain the part. It is necessary to ensure that these deviations stay compatible with the maximal admissible strains of the material.

The RTM preform injection strategy is defined by the planning department. The injection strategy includes the definition of injection cycles, the location and number of vents and injection gates.

6 Numerical simulation model

The numerical modeling used here is based on two simulation tools: Samcef® and Pam RTM® [16]. In order to associate results between simulations, the same meshing has been used in both calculation codes.

Using the Pam RTM® software, the resin injection into a preform is simulated. This simulation calculates the start and finish times for filling the elements of the mesh.

The cooling and assembly phases are simulated with the Samcef® software. For this, a temperature variation from 175°C to 20°C is then introduced to the position of certain nodes of the part is imposed. From these limit conditions, the state of residual stresses is calculated. By using the different numerical simulation values taken from Pam RTM® and Samcef®, post-processing is carried out, and it is proposed to calculate three different criteria. Using these criteria the performance of the manufacturing solution used to produce the spar could be evaluated.

6.1 Characteristics of injection simulation

The preform injection time is obtained from an adiabatic and isothermal simulation at 175°C. The location of the injection gates and the vents is shown in Fig. 6. Injection pressure is 7 bar. To facilitate resin flow into the preform, a depression of 1 bar is imposed at the vents. The main characteristics of this simulation are given in Table 2.

Table 1 Description of the different zones of the spar

Zone no.	Length (mm)	Thickness (mm)	No. of layers	Fiber rate (%)
1	100	6.012	36	50
2	1,000	5.01	30	50
3	1,000	4.008	24	50
4	1,000	3.006	18	50

Table 2 Main characteristics of the numerical simulations

Part discretization	
Element type	Shell (3 nodes)
Element size	2.8×1.0×2.7 mm
Number of elements	16,120
Process parameter	
Initial temperature	175°C
Final temperature	20°C
Pressure injection	7 bar
Depressure	1 bar
Gel time resin (175°C)	32 min
Resin viscosity	0.2 Pa s

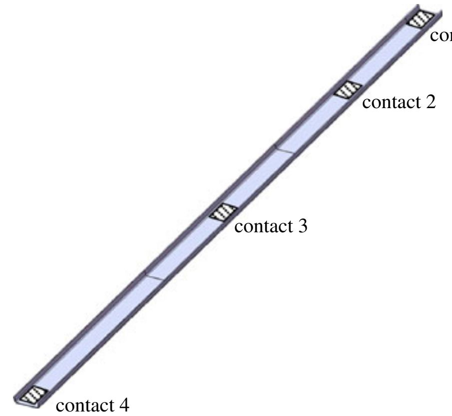


Fig. 7 Position of contact surfaces

6.2 Characteristics of thermomechanical simulation

The Samcef® simulation tool defines the thermomechanical characteristics of a unit cell made up of unidirectional continuous fibers polymerized by the resin. Their mechanical behavior is orthotropic. Moreover, a linear behavior of the material is assumed (i.e., only elastic strain is taken into account). The main characteristics of this structure are shown in Table 3.

The thermomechanical simulation is composed of two stages. The first consists of bringing the temperature of the part from 175°C (corresponding to the polymerization temperature of the RTM cycle) to 20°C. The second stage is the simulation of the assembly operation. Based on the position of the contact surfaces of the spar with the adjacent parts in the tail unit, certain nodes of the mesh are fixed in position. The locations of these different surface areas are indicated in Fig. 7.

This approach does not take into account the local stresses undergone when assembly is realized by riveting. In this study, it is only considered the global mechanical behavior of the spar in the tail unit and not the detail of the local mechanical stresses. The riveting operation will need to be checked later and will not be covered in this study.

7 Results

7.1 Analysis of the criteria

According to the geometrical configuration chosen for the simulations, the clamping conditions and the thickest thickness are located at $Z=0$. The five gates are evenly distributed along the profiles from the origin to the end, which is 3.1 m away. The eight vents are distributed along both sides of the spar between the gates. The positions of the gates and the vents are shown in Figs. 8, 10, and 12. The total duration of the injection phase is 1,061 s (about 18 min). Compared with the characteristics of the resin selected and the RTM injection temperature, the injection time is very much less than the crosslinking value for the resin.

In the map shown in Fig. 8, note that the evolution of criterion Cr_1 is identical between each injection gate. Moreover, if we observe the zone where $Y=0$, along the profile, it could be noted that the resin flows regularly in the preform. This is an important result, as it means that the variation in thickness has only very little influence on injection. This phenomenon can be explained by the identical value of fiber density for each of the different zones of the part.

On the other hand, on the vertical parts of the profile, in the alignment with the injection gates, values for the

Table 3 Thermomechanical characteristics of unidirectional ply–resin structure

	x (fiber direction)	*y*	*z*
Young modulus (MPa)	106,000	8,000	8,000
Poisson ratio	0.35	0.3	0.3
Thermal expansion coefficient (1/°C)	$-1.2.10^{-6}$	34.10^{-6}	34.10^{-6}
Shear modulus (MPa)	4,000	4,000	4,000
Tensile strength (MPa)	1,270	42	42
Compressive strength (MPa)	1,130	141	141
Shear strength (MPa)	98	98	98
Mass density (kg/m^3)		1,530	

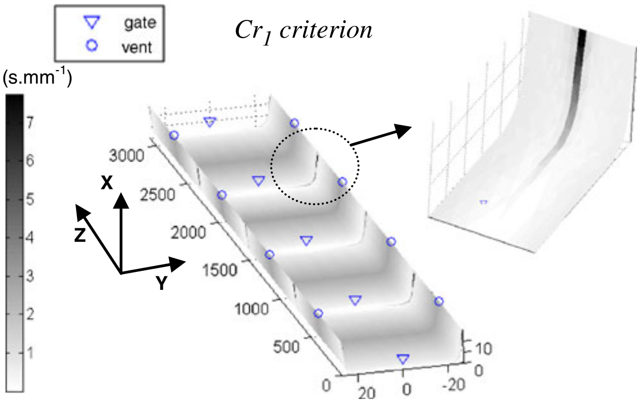


Fig. 8 Map of criterion Cr_1

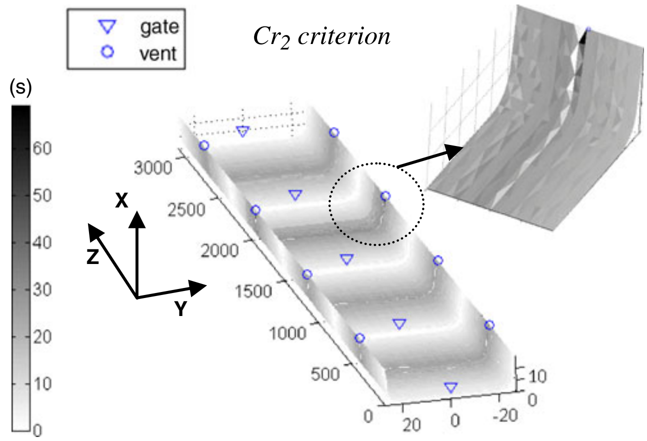


Fig. 10 Map of criterion Cr_2

criterion are widely scattered. In these zones, the criterion reaches its maximal values. This represents a progression of the flow resin, first of all in the horizontal zone of the profile in the direction of the vents. After this, when there is an increase in pressure, these zones are finally filled by flowing back of the resin. The histogram of all the element values of the criterion, in Fig. 9, shows that the mean of the Cr_1 values are low (1.43). There is little scattering of values (standard deviation of 0.73). Some extreme values could be observed for the criterion which is mainly due to the phenomenon of resin backflow.

Concerning criterion Cr_2 (Fig. 10), the zones where the criterion is greatest correspond to the zones close to the vents (z=388; 1,163; 1,938; and 2,713 mm). In these zones, along the cross-sectional area (z normal orientation), it can be noticed that there are some wide variations in values. This is due to the increase in pressures in the preform, which disturbs the resin flow. The last zones to be filled in the preform are located close to the vents, which would seem to be normal. Moreover, during the injection simulation, the maximal time for filling all elements is 70 s. This time is relatively short and leads us to conclude that the injection strategy is well adapted. Figure 11 shows the histogram for this criterion. Note that the mean value and the standard deviation are low (respectively 13.1 s and 7.3 s).

Criterion Cr_3 is deduced from the stress state along the part after the cooling phase then the assembling of the spar into the tail unit is done. Morever, the level of variation on the map for the Hashin criterion, Fig. 12, ranges from 0.76 to 0.88. Given these values, failure level for both the fibers and the resin is not reached. There are four zones for which the criterion is lower; these zones correspond to the locations of the contact surfaces with the adjacent parts (z=30; z=630 mm; z=1,623 mm; z=3,080 mm). The value of the criterion is high where the spar is clamped to the fin (z=0 mm). The variation in profile thickness seems not to have any effect on the variation in the stress state along the profile. This point is confirmed by the histogram in Fig. 13, for which the standard deviation of Cr_3 criterion is very low (0.01).

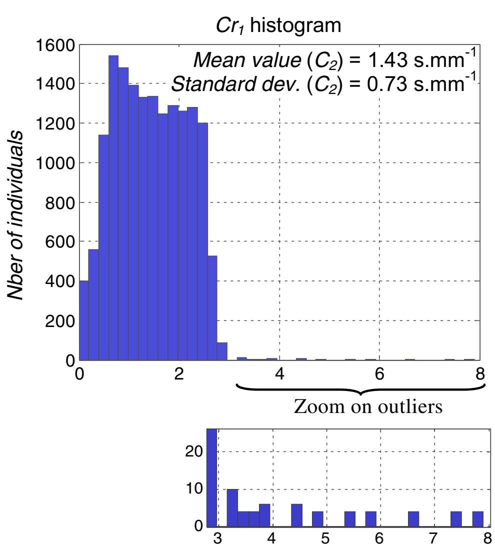


Fig. 9 Histogram of criterion Cr_1

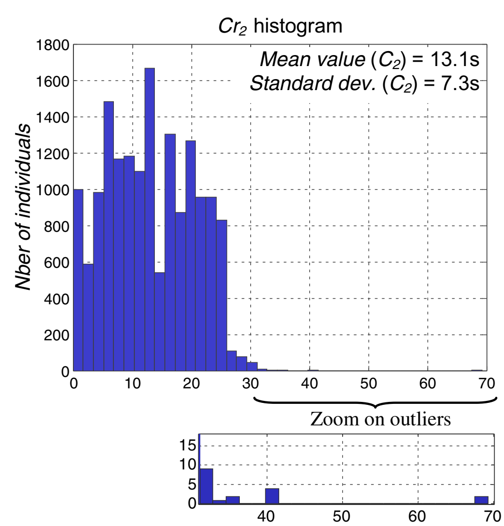


Fig. 11 Histogram of criterion Cr_2

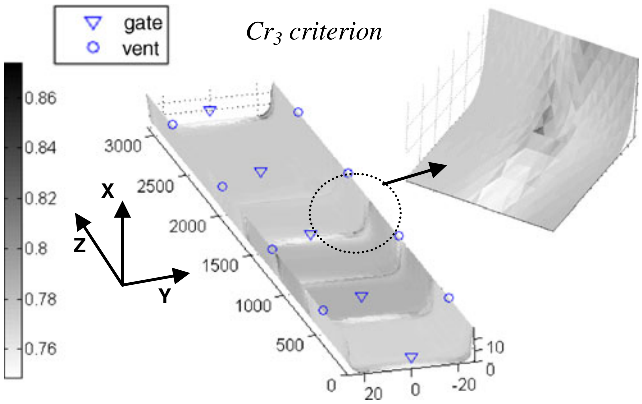


Fig. 12 Map of criterion Cr_3

7.2 Analysis of coupling between criteria

The previous calculation allows to analyze both the position on the part of the criteria values and their distribution. This information is important but if an area of the part simultaneously combines high values of the Hashin criterion (Cr_3) and important values of Cr_1 and/or Cr_2, these accumulations can lead to a decrease of mechanical performances. To take into account this phenomenon, the analysis of the coupling between criteria is proposed. The identification of the coupling is based on the identification of element which exceeds a threshold for every criterion. The threshold values can be defined according to the designer's experience, to the histogram analysis of the distributions of values of criteria. In this studied case, the values adopted are given in Table 4. They were chosen according to the distribution of values for each criterion (Eq. 8).

$$Y_{Cr_j} = \mu(Cr_j) + \sigma(Cr_j) \tag{8}$$

with $j \in \{1,2,3\}$

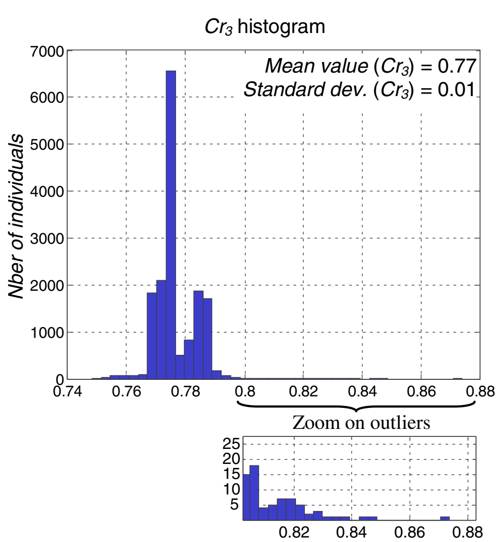


Fig. 13 Histogram of criterion Cr_3

Table 4 Thresholds selected for consideration of coupling between parameters

	Y_{Cr1}	Y_{Cr2}	Y_{Cr3}
Yield values	2.2 s mm^{-1}	20.4 s	0.78

$\mu(.)$ Corresponding to the mean of criterion Cr_j
and $\sigma(.)$ The standard deviation of criterion Cr_j

The operation consists in identifying the element which exceeds a Hashin value of 0.78 and cumulates a Cr_1 or Cr_2 value respectively upper than 2.2 s.mm^{-1} or 20.4 s. If a coupling is identified, the corresponding element has a level equal to 1, otherwise, the value of the element remains zero. The relationship used is given in Eqs. 9 and 10. It is then defined as a criterion R_{Crji} corresponding to the estimated risk for every criterion j associated to the element i.

$$\begin{aligned} &\text{If } Cr_{ji} < Y_{Crj} \\ &\text{then } R_{Crji} = 0 \\ &\text{else } R_{Crji} = 1 \\ &\text{End} \end{aligned} \tag{9}$$

Then, the risk value R is calculated following the relation 10.

$$R_i = \max(R_{Cr3i} \times R_{Cr1i}, R_{Cr3i} \times R_{Cr2i}) \tag{10}$$

Such as : $i \in N$ and $i \leq n$
n number of elements
$j \in \{1, 2, 3\}$

The results of the coupling analysis are plotted on a global mapping given in Fig. 14 (upper). The mapping of every criterion (lower part of Fig. 14) identifies the criteria responsible for the coupling. According to the results obtained, areas of coupling values are localized for z values ranging from 800 to 1,300 mm. The coupling areas are located within areas with high values of criteria. As it could be observed in Fig. 14, the levels of Cr_1 and Cr_2 are over the yield limits between 1,100 and 1,500 mm. This phenomenon can result in a loss of mechanical performance and therefore a potential risk of rupture. The use of such a tool is quite relevant in the case of analysis and alternative choices of industrialization. In this case, the designer wants to select the best configuration of the tool which leads to minimize the risk of the mechanical property decrease. The strategy consists to gradually reduce the threshold values of each alternative and the best solution corresponds to one limiting couplings for the lowest threshold values.

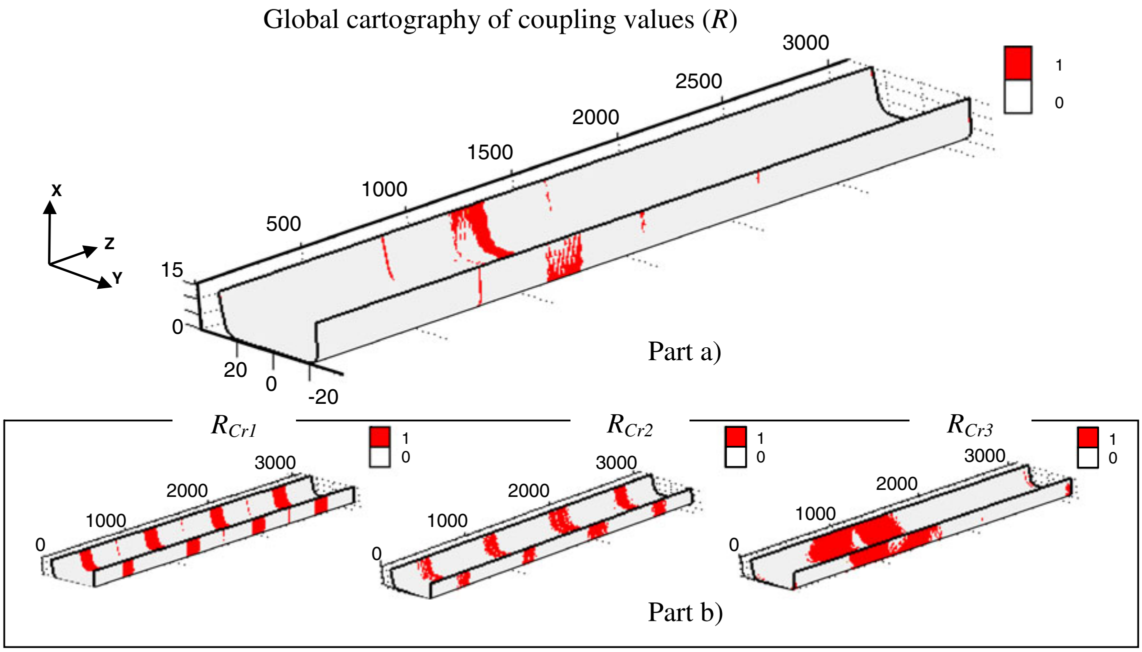


Fig. 14 Analysis of the coupling value for every criterion (*part a*), and identification of the different sources of risk (*part b*)

7.3 Assessment

Analysis is carried out of the different evolutions of the three performance criteria relating to the profile of the part. The criteria levels remained below acceptable limits. The design of the tooling and also the pressure/time cycle used are thus validated by the set of maps for the Cr_1 and Cr_2 criteria. There are some extreme values that could be pointed out for the first two criteria (Figs. 9 and 11), which suggest that the tooling could be improved, for example, with added vents.

The Cr_3 criterion has a high mean value close to 1. This suggests a lower safety margin in relation to the failure of the component. Knowing that the design choices are fixed, one possibility for increasing this margin is to look again at the injection phase, in particular by decreasing the injection temperature of the resin. The geometrical manufacturing deviations resulting from the cooling phase would then be less. That leads to decrease the stress state at the end of the assembly phase. For example, a decrease of 15°C, bringing the injection temperature down from 175°C to 160°C, modifies the value of criterion Cr_3 from 0.71 to 0.41. However, these modifications would involve a change in the characteristics of the resin (slight increase in cross-linking time and viscosity).

The part used here is derived from an industrial example studied with an industrial partner. Although the injection strategy is different for confidentiality reasons, the range of deviations of manufacturing, injection temperatures have the same order of magnitude and can validate the different simulations.

The validity of all results is mainly based on numerical simulations. It is necessary to ensure a good accordance between numerical results and the real parts. It is obvious that many parameters have significant influence on the overall behavior of the injected part such as permeability, uncertainties during the construction of composite materials (e.g., fiber orientations), the movement of fibers during the injection, to cite some but a few. All these phenomena cannot be considered in a design approach for manufacturing and assembly realizing in the early phases of design. However, the selected parameters [4, 13], are available very early in the design cycle and help to explain most phenomena related to geometric deviations and volumetric impregnation deviations.

It is important to remain that the main objective, in this phase, is to bring to the designer decision elements in order to orientate and validate its choices among all the feasible solutions.

8 Conclusion

In aeronautics, the main challenge is to optimize the mass of every component of the airplane. This objective aims to reduce the safety factor typically used on parts to ensure their mechanical strengths. It is important to offer engineers the tools and methodologies adapted to these new challenges.

The focus of this paper is to propose a general method for validating the choice of both design and industrialization of parts in composite material obtained by RTM process.

Usually, the manufacture by RTM is generally associated with the optimization of the injection phase (tooling configuration to ensure minimal residual porosity) and then optimization of the curing phase (to minimize the geometric deviations of the part).

The originality of the proposed method comes not only from the consideration of the injection and the curing/cooling but also the assembly phases of the part performed by existing commercial software. The main goal then is integrating the industrialization constraints to improve decision support in the design phase, for example, to reduce the mass or the manufacturing cost. This approach corresponds to a design for manufacturing one.

To make it possible, the performance of a solution is defined through three criteria related to the RTM mold (Cr_1) to RTM Cycle (Cr_2) and the failure criterion of Hashin (Cr_3) and the coupling analysis between them. The failure criterion of Hashin has priority in the analysis. Indeed, in the simulation of assembly, the Hashin criterion is near or exceeds unity, this means that there is an important risk of failure of the component, and that leads to eliminate the potential solution. In a second step, criteria Cr_1 and Cr_2 identify areas where there could be volumetric impregnation deviations. Different criteria are analyzed both through a histogram value to identify outliers and through maps to locate the risk areas. The location of areas with high values of criterion allows the designer to know the location of areas combining both high values of Hashin and risk of volumetric impregnation deviations. These two phenomena lead to a drop in mechanical performance of the part and increase the risk of failure.

The operation of the global mapping associated with the sensitivity analysis of threshold values of criteria is used to identify the best solution. The use of such maps allow to define several possible scenarios and then to target the modifications to be considered during the manufacturing phases. Thus, if:

- A map of Cr_1 has too important values, this suggests reviewing the location of the vents and the gates,
- A map of Cr_2 has too important values, this suggests modifying the RTM cycle (pressure/time),
- A map of Cr_3 has values close to 1, this suggests modifying the RTM cycle (temperature)

The methodology and results presented in this paper open several perspectives and applications. The different maps of criteria could be used to facilitate the reading of results from numerical simulations and understand linkages between criteria. Maps could be used to ensure a common understanding for all stakeholders in the design cycle and industrialization and thus improve trade-off between these different actors. As the risk of residual porosities is clearly identified on the maps, these information represent a useful tool for the non-destructive tests allowing to target the area to verify and then minimize the needed time for validating the manufactured part.

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