INDUSTRIALISATION OPTIMISATION OF RTM PROCESS APPLYING MANUFACTURING PROCESS SIMULATION

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ABSTRACT: Today's and future helicopter programs require an optimised development and industrialisation phase, complying with "first-time-right" requirements. It demands a detailed understanding of the processes at a very early part design stage to accelerate feasibility studies and to reduce prototype numbers and costs. Thus, Manufacturing Process Simulation (MPS) for composites can be considered as a strong tool to control processes and to facilitate development and industrialisation.
The paper offers an overview of currently available and used manufacturing process simulation tools for RTM processes, describing their applicability in development projects and within industrialisation, ramp-up and serial production phases.
A recent case is also presented in more details. It deals with heating and curing modelling of an RTM part. That case is presented through real MPS applications for rotorcraft parts out of composite materials. The different features will be explained to focus on industrial end-user needs. Actual technical blocking point issues as well as the need for a new design chain will be addressed.
KEYWORDS: Industrialisation, Manufacturing Process Simulation (MPS), RTM.

INTRODUCTION

New manufacturing technologies such as liquid composite moulding or fibre placement technologies focus in some extend on direct manufacturing of integrated structures. New equipment for automated manufacturing is being developed to directly lay-up and manufacture composite structures. Machine parameters will define structure quality and properties. That makes a change compared to a classical approach in composite manufacturing, where detailed investigation on material properties generate the baseline for later part design and sizing [1]. Drawback of that approach towards automation is an increase in industrial risks, due to influencing and determining quality and properties, not yet addressed within baseline material assessments. Parts are directly manufactured to shape with limited possibility to manufacture flat laminates for coupon testing. And non-conformities of the component may be observed very late. If the first prototype doesn't comply with specifications, it is to be redesigned at a very late qualification stage. The project is then charged with high additional costs.
Eurocopter has identified Manufacturing Process Simulation (MPS) as a mean of risk reduction by systematically creating links between the different structure qualification levels. The MPS term designates a range of physically-based simulations to predict process feasibility, the best manufacturing parameters and possible deviations or irregularities. MPS can avoid time and costs occurring through classical industrialisation methods. In that extension, MPS is thus considered as industrialisation process optimisation. Primarily developed for metallic material transformation processes, improved technical capabilities enable simulation tools to be applicable to

composites processes (new behaviour regulations, new numerical capacities etc.). Yet, industrial maturity still remains to be proven.

This paper presents the different MPS types identified for composites helicopters part manufacturing. An application is then given of a whole heated RTM process simulation. Finally, the conclusion offers a recommendation glossary to enable correct MPS implementation at industrial level.

MANUFACTURING PROCESS SIMULATIONS

Each step of the manufacturing process (cf. Fig.1) has its own specificities and parameters related to certain physical behaviours. Reinforcement forming, e.g. fabrics or unidirectional lay-ups, is dominated by its mechanics. Associated MPS will give outputs concerning general forming feasibility, fibre orientation as well as process definition parameters (best boundary conditions). Infusion is flow-dominated. MPS helps validating the tooling strategy as well as the resin selection. Temperature repartition in closed space is CFD-dominated. The associated simulation will offer the best sensor positions and the best part arrangement in the oven or autoclave. Curing simulation is a thermo-mechanical calculation governed by resin cure kinetics. Corresponding MPS enables to define the heating cycle to be applied.

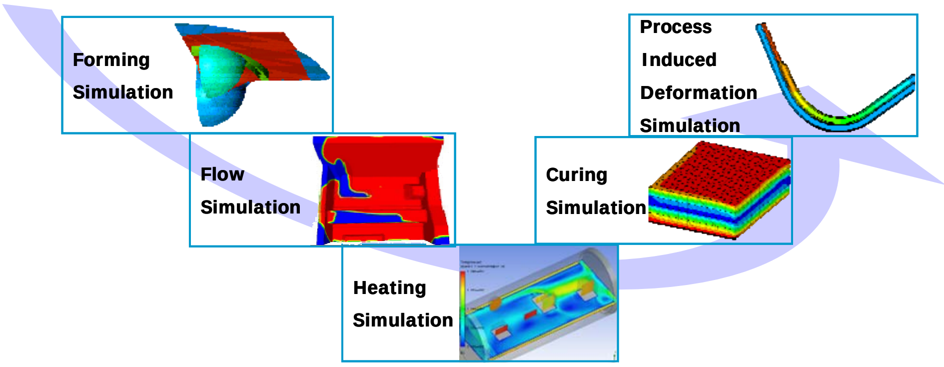

Fig. 1 Overview of manufacturing process simulations for composites

Those simulation modules are chronologically coupled and create an MPS chain needed for right Production Engineering.

Draping and Forming Simulations for Preforming

Two MPS procedures are related to the preforming manufacturing stage. Draping simulation geometrically models reinforcements based on strong hypothesis concerning the behaviour of a woven fabric [2]. For instance, fibres are considered as inextensible, sliding and frictions are not taken into account and the fabric has only one deformation mode. On the other hand, FEM physically-based forming simulation [3, 4] takes into account the complete multi-solid domain (materials, tools) with contacts between the solids, and realistic boundary conditions (temperatures, speeds, pressures and forces).

Infusion Simulations for Liquid Composite Moulding

LCM is a generic term for a process family in which a preform is impregnated using a polymer matrix as a liquid resin. The configuration of resin sources and vents and their history compose the infusion strategy. But finding the best strategy is not trivial and a complex part often requires many tests. A bad strategy can lead to partial infusion or a great amount of lost resin. The step-related MPS is an impregnation simulation based on

FEM model of fluid flows through porous media. This flow rate governed by Darcy's law depends on applied pressure, fluid viscosity and fibre permeability. This model is implemented in diverse scientific and commercial software. It's well adapted to injection processes in hard tool units like RTM. Development continues for infusion simulation where mechanics (compression) and reinforcement permeability are linked [5].

Thermo-mechanical Simulation for Modelling of RTM parts

To control the thermo-mechanical chain is of utmost importance to optimize manufacturing time of RTM parts. But the temperature repartition inside the part and the tooling is a complex analysis that is still executed on experiment level only.
The heat transfer in closed mould considers classical thermal transfer assumptions between solids. If the part is complex with a huge dimension, the tooling is massive and takes long to reach desired temperatures. Heat transfer is not linear anymore. As a result, the real thermal cycle at part level can differ widely from the part temperature prescribed cycle (or target cycle) as defined at part level in industrial procedures. The command cycle becomes thus very complex to define and needs much experimental iteration. It leads to longer industrialisation and production. MPS tools help to define the right process cycle taking into account the target cycle at part level. A simulation chain defines the correct process cycle of the heating device. That simulation chain includes 4 chronological simulation stages which have to be linked together by boundary conditions (B.C.) they use. The following figure illustrates that concept.

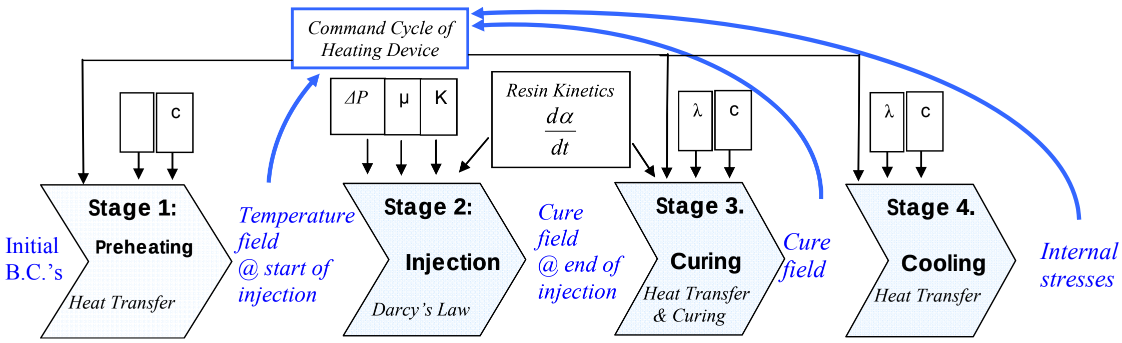

Figure 2: Thermo-mechanical simulation chain and transfer of boundary conditions

On top of the meshed geometrical model, inputs correspond to classical thermal parameters (conductivity and capacity) together with resin kinetics & viscosity, the preform permeability and the pressure difference applied during impregnation.
The main output will be the field of cure extend and internal stresses within the part at the cycle end. Hence, the command cycle is defined to ensure a complete and homogeneous curing of the resin, a good part quality and less internal stresses. The complete manufacturing time is also optimized before manufacturing the first prototype.
Note that in case of open mould processes (like pre-preg in Autoclave, RFI or VAP) fluid dynamics ensure the energy exchange. In that case, heat transfer becomes much more complex. In an autoclave, an oven or in a Quickstep device [6], the temperature repartition depends on the turbulent fluid circulation. Thus, associated MPS must integrate a CFD simulation module.

APPLICATION ON HEATING & CURING OF A RTM LONGERON

The thermo-mechanical simulation chain is already implemented for the RTM process in a united digital platform called PAM-RTM™ (ESI Engineering System International). This analysis tool is available as stand alone software or as an integrated

feature in CATIA V5™. It's possible to conduct a whole heated RTM manufacturing simulation. The Finite Element programming is here based on classical heat transfer equations (for the heating) and on the Darcy's equation (for the filling simulation).
A first application by Eurocopter Deutschland dealt with an I-section helicopter longeron. The objective of simulating the whole RTM process is to plot history parameter fields such as temperature, filling and cure. At the tooling design stage, different impregnation strategies can be virtually tested. An impregnation strategy is the position of the inlets and vents in the tooling, together with dynamic ruling of their actuators (open and shut of inlets for instance). The best defined strategy is the one that doesn't generate any defect (dry spots), and minimises impregnation time and quantity of needed resin. Thanks to the simulation tool, the best strategy is thus identified and implemented in the final tooling design. The following figure shows the model of the industrial part. It consists of three component types: dry preform, mould and press. The model takes into account all parts with thermal influence. It means that the model boundary even includes compression plates of the hydraulic press.

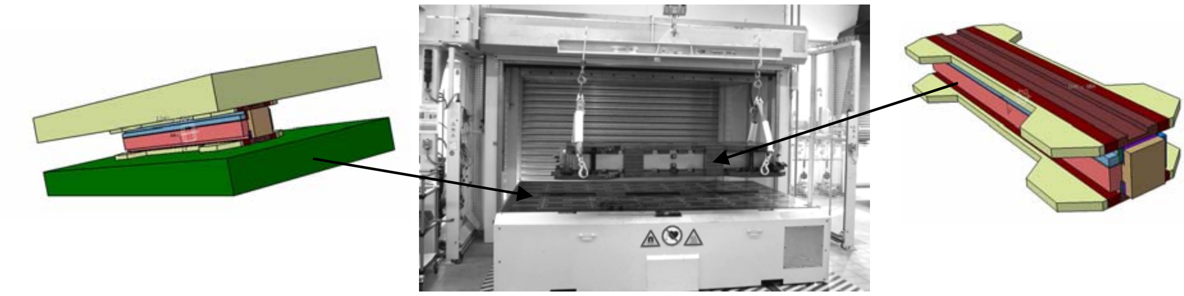

Fig. 3: Models and the real system (press is open to see the tooling)

The permeability field takes into account the presence of uni-directional reinforcements on the beam flanges giving a higher longitudinal permeability [7]. The resin used here is a classical epoxy resin for aeronautical application. Its kinetic and related modelling is available in literature [8]. As the real process, the simulation is divided into three stages:

- preform heating using the press through the mould (preheating)
- resin injection into the mould
- preform curing

The press heats the mould from room temperature till 120°C. A temperature field is applied to the outer press surfaces. For all the other outer surfaces in contact with air, a natural convection (with a 10 $W.K^{-1}.m^{-2}$ flow) is applied as boundary condition. The temperature distribution in the entire model resulting from the preheating simulation is used. During the infusion stage an inlet pressure history at the injection port is applied. Desired results are temperature distribution during filling, filling time, quantity of resin and degree of cure. The infusion time differs between simulation and reality of approx. 12%. During that stage, the preform starts to cure but at a weak rate. Temperature and curing rate are used to initialize the curing step. To cure the resin is characterised by a temperature rise till 180°C.
The figure n°4 illustrates the results. Heating simulation demonstrated a good correlation with the prescribed command cycle (in blue). A difference is depicted between external and internal (at preform level) temperature, the latter being impossible to measure. Finally, a clear potential of cycle time reduction compared to the prescribed thermal cycle seems possible.

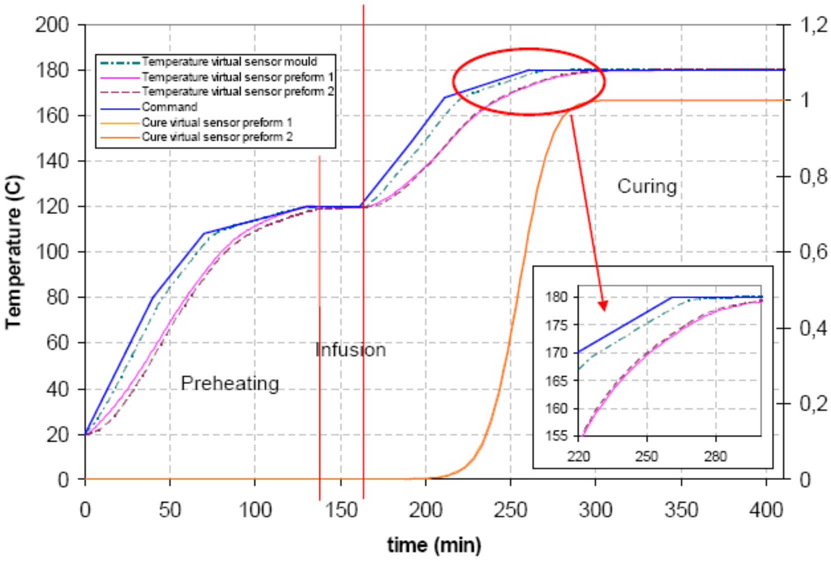

Figure 4: Temperature and cure during the complete cycle

CONCLUSION

Future composite materials, processes and technologies for helicopter applications will be in the spotlight in terms of cost and weight requirements. Automated technologies (e.g. liquid composite moulding, fibre placement) have been identified as very promising. With the help of fitted simulation modules, risks and costs attached to the use of that new technology will decrease. MPS usage methodology facilitates the management of late design changes and increased process understanding and maturity. MPS is considered to support industrialisation process optimisation of composite parts, thus time to market of new technologies can be shortened.

A broad use of MPS still faces several obstacles. For example, physical properties used within MPS are still not included in classical data sheets defining materials, i.e. the mechanical behaviour of a reinforcement and its drapability, preform permeability according to layer stacking and shear angle of each layer, thermal conductivity according to curing ratio etc. Above all, a new internal organisation appears mandatory to enable an earlier accountability of the manufacturing parameters at design stage.

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