Correction of manufacturing induced distortions of automotive composite parts with simulation

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Abstract: One of the biggest challenges for designers and manufacturers of composites-parts nowadays is to ensure that designed parts can be produced within tolerance that will cause no issue at the assembly stage. This paper that focuses on automotive applications of composite materials for structural parts will first review adapted manufacturing processes for mass production and then describes involved physics in resulting shape distortions.

Computational techniques developed to predict manufacturing-induced residual stresses and shape distortion of composites parts made of continuous fibers and thermoset matrix will be presented supported by an industrial example.

Knowing how the part will distort after manufacturing is a first step. The second one consists in finding a solution to these geometrical defects in regards to the designed part. Simulation can then be of a great help in determining the proper process parameters and new mold geometry to reach tolerances. However this paper intends to demonstrate that only the simulation of the complete manufacturing chain can validate a solution to distortions.

Keywords: Composites manufacturing simulation chain, geometrical distortions, Product/Process design

Introduction

Environmental awareness and regulation, fuel consumption as a selling argument and the need for an increased autonomy of electrical vehicles are pushing automotive industry to develop lightweight designs. Composite materials, lighter than steel and Aluminum, are already widely developed in automotive industry with short or long fiber materials for non-structural components. The extension of the use of composite materials to structural components with high mechanical requirements in replacement of metallic parts is today the challenge.

The first criteria to reach when switching from metallic to composite component for structural components is a non-regression in mechanical behavior under static and dynamic loading. Mechanical behavior of the composite part will of course depend on the product design (material selection, ply sequence and sizing, etc) but also on its manufacturing process. Indeed, the “built part” will always contain some “defects” (as porosities, fiber shearing, residual stresses, variation in thickness distribution, etc) in regards to the designed part. These local imperfections will impact the performance of your product. The importance to account for the interdependency between product design and process design has already been clearly identified by the automotive industry with the growing use of advanced metallic materials (HLE, Aluminum); the introduction of high performances composites materials in the automotive industry strengthens the need for a product/process design approach.

This paper will focus on a specific defect that is the geometrical distortion observed at the end of the manufacturing process. Indeed, the non-respect of geometrical tolerances results into assembling stresses that highly impact the mechanical behavior of the final product. It is thus very important to minimize these geometrical defects. A numerical approach to prevent spring-in upfront in the product development process will be presented.

Composites manufacturing processes adapted to mass production

High performance involves most of the time the use of continuous fiber materials for which design and manufacturing know-how and experience come mainly from aeronautic industry. However, technology transfer from aeronautic to automotive industry is not so simple. Specific constraints as the production time cycle and the process automation have to be taken into account in mass production of automotive components. Moreover, the cost of the finished part that is directly linked to the material and process cost will determine the selling price of the vehicle and thus is a parameter of the highest importance. Finally, considering vehicles life cycle and recent regulations, recyclability cannot be neglected.
To summarize, the use of composite material for structural parts in automotive mass production is subject to the following constrains:

- Production time cycle
- Process automation
- Cost of the finished part
- Recyclability
- Performances (no regression allowed versus metallic parts)

The need for process automation and the production time cycle requirements (thousands of parts per day) eliminates manual lay-ups (textile or prepregs) as well as tape or yarn laying or filament winding processes widely used in aeronautic industry. Processes based on non-continuous fibers (short or long fibers) as Sheet Molding Compound (SMC), Bulk Molding Compound (BMC), Glass fiber Mat reinforced Thermoplastics (GMT) and Long Fiber reinforced Thermoplastics (LFT) are complying with time cycle constraints but are secondary options because of the usual decreased mechanical performances compared to continuous fibers processes. Finally, prepregs and particularly thermosets that are quite expensive with costly storage conditions and short life duration are not adapted to the industry challenges.

Thus a “natural” selection of adapted manufacturing processes for mass production of structural components can be done. It leads to the two main following processes:

- Thermoplastic pre-pregs thermoforming (thermoplastics remain quite expensive however they offer non-neglectable recyclability possibilities and do not require costly storage conditions). A schematic of the manufacturing chain is represented in figure 1.

- Textile automated preforming (stamping) followed by resin injection in closed molds (RTM: Resin Transfer Molding). A schematic of the manufacturing chain is represented in figure 2.

Both manufacturing chains generate stresses in the part that will make it distort after demolding. In order to reach shape tolerance requirements, most of the time the geometry of the tool must be compensated.

For simple parts (simple in terms of complexity of the geometry and/or material layup) geometrical distortion can be minimized by respecting recommendations on manufacturing process parameters as well as product design rules coming from either empirical approach, experience or rules of thumb. However these approaches will not be sufficient when dealing with more complex parts and besides the respect of product/process rules, warping and/or spring-in will still be observed after demolding. It then usually takes lots of testing modifying process parameters and cycles compensating mold geometry to obtain a part within desired geometrical tolerances and respecting all minimum quality criteria for acceptance. These trials are time consuming and very costly. Performing these trials through simulation is of the highest interest because of the consequent development time and cost reduction it represents. Through the use of simulation, virtual trials can be multiplied for a better understanding of the influencing parameters and thus an optimized solution to the geometrical distortions.

However, industrial adoption of simulation for geometrical distortion prediction and correction is only possible when trusting the simulation tool. A secondary criterion of acceptance is the ease of use of the application that should not complicate the task of the engineers. Whereas Finite Element Analysis (FEA) is already well adopted in the industry for spring-back prediction and correction of metallic
parts and besides several solutions already available in the market for composites application, full industrial adoption (meaning replacement of physical trials by numerical trials as what we can observe with metals) has not been achieved.

This observation led ESI as a specialist in the physics of the materials and leader in the simulation of the manufacturing chain of composites materials made of thermoset or thermoplastic matrix and continuous fibers, to conduct for the last 4 years R&D projects focusing on shape distortion of thermoset composites materials. A dozen of industrial projects completed in the last 2 years validated the developed approach and resulted in the industrialization of the software solution named PAM-DISTORTION as a complement of the existing simulation chain (PAM-FORM and PAM-RTM).

**Shape distortion of thermoset composite parts**

We will now be focusing on the manufacturing chain described in figure 2 in which several layers of dry textiles are placed in a forming tool to obtain the so-called preform that is then placed in a RTM mold for the injection of the thermoset resin and curing (that might start during the injection) before demolding.

Warping and spring-in of the final product are a consequence of the stresses induced by manufacturing. Stresses for its major part are created in the curing stage during which the thermoset matrix will first go from liquid state to rubbery state and then from rubbery state to glassy state. The uncured part is heated to reach cured temperature and then cooled down to room temperature. During this cycle two nature of strains that directly impact geometrical distortions are observed:

- Thermal strains due to the change of temperature of the resin and the reinforcement. These strains depend on the phase of the resin: thermal expansion of the resin is highly different in the rubbery phase than in the glassy phase.

- Chemical shrinkage that occurs due to phase transformation of the thermoset matrix that goes from liquid to glassy (solid) state.

The release, during demolding, of the stresses generated during curing results in the geometrical distortion of the final product.

A simple cure cycle and the physical phenomena observed (phase transformation, degree of cure and temperature evolution) are summarized in figure 3.

The basics for accurate prediction on how the part will deform is an accurate prediction of stresses. Accurate prediction of stresses can only come from a complete simulation of the involved physics. Most of the available software on the market neglect phase transformation involved in the process, which means that evolution of physical properties of the resin during curing is not considered and that chemical shrinkage is not taken into account. This first simulation approach is not useless, it can give first indications on distortions. However, it can also lead to the conclusion that simulation tools in general cannot properly determine how your part will deform.

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**Temperature**

--- Glass transition temperature

--- Degree of cure

Figure 3: Properties evolution during a simple curing cycle

The second approach as integrated in PAM-DISTORTION aims at considering all physics involved in curing process but still allowing simplified first approach when data are missing. Indeed, the counterpart of this second approach is the need for material properties of the thermoset resin in rubbery as well as in glassy (solid) phase. Whereas glassy data are usually known, obtaining rubbery data might be more tricky: they can be estimated from glassy data based on experience or they can be obtained through additional material testing. Material data being the core input of simulation and standards being missing for some of the characteristics (as for instance the coefficient of chemical shrinkage), it is very important to follow a step by step approach for a proper use of the simulation tool on industrial parts. First step is to get confident in the material data used. This first step goes through simple geometrical samples that will be used to validate and tune material data to be entered in the application. Once material data used validated, all physics being considered in the software tool, industrial cases can be analyzed with confidence.
Simulation of geometrical distortion

This chapter describes the three main stages of the simulation of geometrical distortion of thermoset composite parts. Whatever the software used (considering that this software account for all the physics involved in the process – see the second approach described above), the three following stages will be respected:

- Creation of a solid mesh of the part;
- Simulation of the curing process to get the temperature and degree of cure history in each location of the part;
- Simulation of the distortion using temperature and degree of cure history computed in the previous stage as an input.

The mesh creation is a critical stage that is also the most time consuming. Two modeling strategies are possible at this stage: whereas each ply of the stacking is represented by one layer of solid mesh; whereas one layer of solid mesh represents several plies. The second option implies an homogenization of the material data that can either be done “manually” or through integrated application within the simulation software. The advantage of that second option is a drastic reduction of the model size (in terms of number of elements) that is an important limitation of some of the existing software in the market. Indeed, whatever the meshing strategy used, lots of industrial cases, in the aeronautic or wind energy industry because of the size of the parts and in the automotive industry because of the geometrical details of the parts, will result in models of several hundred thousands of elements. Most of the software will not have the computing capacity to deal with such model size and thus will opt for an analysis by section instead of looking at the whole part. This section approach that is just a result of computing limitations has an impact on the accuracy of the results.

Once the mesh is created, it will be used to simulate the curing process. The curing simulation is a thermochemical analysis to compute the temperature history as well as the degree of cure history in each location (each node) of the part. This simulation should consider the exothermic aspect of the curing process. Typical curing results obtained on a fuselage panel (mesh on figure 4) are represented on figure 5 and 6.

The final step is the computation of the geometrical distortion, warping and spring-in, of the part. It goes through a mechanical analysis that account for thermal and chemical internal stresses (using temperature and degree of cure history computed in the previous step, the curing simulation) and external loading (as pressure in the autoclave, contact with the mold, etc). One result of the computation is the normal or directional displacement of each node of the model, with or without applied locking boundary conditions.

Figure 4: Solid mesh of a representative section of an aeronautic fuselage panel for distortion analysis

Figure 5: Temperature contour issued from the curing simulation and displayed on a section of the fuselage panel

Figure 6: Temperature history (of one element of the model) during curing with a pick due to the exothermic reaction.
Green curve: imposed temperature on part surface
Red curve: Computed temperature in a mid-plane location
There are then two possible conclusions to the distortion simulation: the part is within our acceptance quality criteria in terms of geometrical tolerances or the part is out of the tolerances to be reached.

In that second case, an iterative simulation process will be used to find a solution. Iterations can be first on process parameters (as for instance modifying temperature cycle of the curing process) to check if distortions can be fixed at a lower cost with changes that would not require a complete re-validation of the model. However, these “low cost” iterations are sometimes not enough and iterations on mold geometry are required. Then, the nodal displacements computed during the distortion analysis will be used to generate a compensated mold through a reverse engineering approach. The final mold that leads to distortion within desired tolerances is most of the time the result of several iterations of mold compensation.

**Distortion simulation as part of a simulation chain**

We have seen in previous chapters that the solution to geometrical distortions that are not in desired tolerances can in some cases only be fixed with new mold geometry, a compensated mold generated from the results of the distortion analysis. It is then mandatory to verify that these geometrical modifications of the mold (wall opening or closing, change of radii and curvatures, etc.) do not badly impact the other stages of the manufacturing process.

Indeed, if we consider the manufacturing chain represented in figure 2, the modification of the mold will pass on preforming and RTM tools as well.

A small change in radii or in the opening of a wall might considerably impact the quality of the preform: using the exact same process parameters but with a lightly different geometry might for instance result into the creation of wrinkles or just modify the fiber shearing.
Mechanical performances of composites parts made of continuous fibers highly depend on the shearing of the fibers. Figure 9 illustrates the impact of fiber angle variation on strength.

In the same way, a key influencing parameter of Liquid Composites Molding (LCM) processes as RTM is the permeability of the reinforcement (preform). This permeability depends on the shearing of the fibers. Indeed, the resin will run faster in the direction of the fibers thus, changes in the shearing of the preform will modify the resin flow pattern during injection and as a consequence might modify the quality of the injection process (as for instance a modification of the filling time) or even the quality of the injected part (apparition of dry zones or increase of porosity level).

To summarize the prediction of warping and spring-in is about stress simulation resulting from curing process but fixing geometrical distortion is an iterative process that needs to consider the entire manufacturing chain because of the interconnected effects between the different stages of the process. Indeed, a mold modification can only be validated through the simulation of subsequent operations as well. Figure 10 illustrates the iterative simulation chain

Conclusion

This paper gave an introduction to geometrical shape distortion with a focus on a typical automotive manufacturing chain for parts made of continuous fibers and thermoset matrix. It explained the different approaches used by commercial simulation software for the prediction of distortions and then described a simulation workflow accounting for all involved physics. The objective of the prediction of distortion might just be in some cases to validate a process but most of the time it aims at finding a solution to distortions that exceed imposed tolerances. The last chapter of this paper tried to demonstrate the interconnections between the different stages of the process and the need for complete simulation chain as proposed by ESI for the validation of geometrical changes in a mold.

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