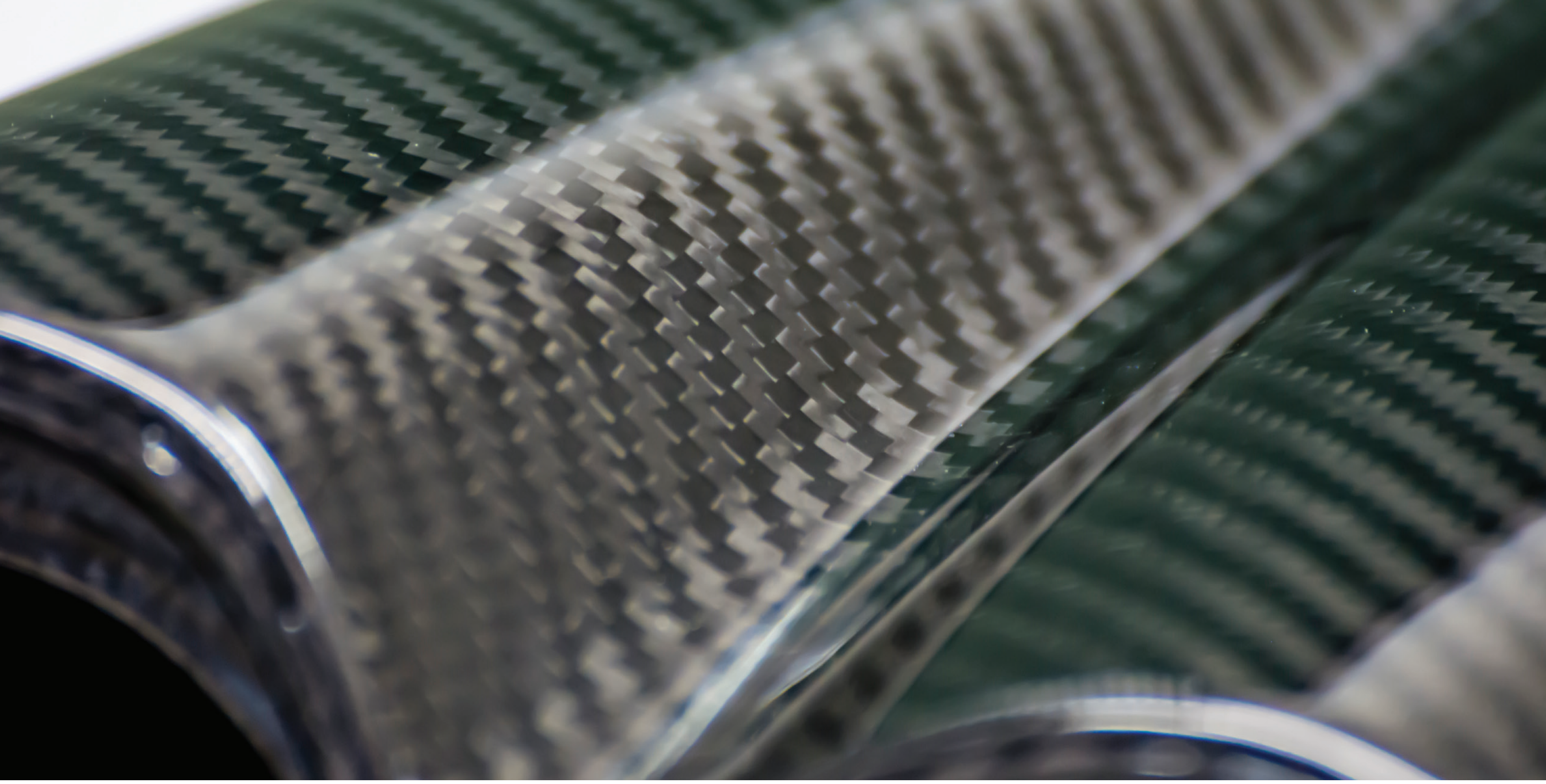

DIGITAL INDUSTRIES SOFTWARE

Streamlining simulation workflow for composites

Improving the performance of an RTM composite B-Pillar by reducing manufacturing-induced defects

Executive summary
Resin transfer molding (RTM) is a commonly used process to manufacture composite parts of complex shapes in large quantities. The manufacturing process of RTM composites is inherently susceptible to defects such as voids, resin-rich areas, fiber misalignment, residual deformations, residual stresses, etc. These defects can compromise the performance of the part. To minimize manufacturing trial-and-error, computer-aided engineering (CAE) tools can be used to find the optimal process-to-performance parameters. Using Simcenter™ 3D software provides a composite manufacturing digital twin, which reduces manufacturing-induced defects and improves performance properties. It also reduces the time-consuming manual engineering work of synchronizing input/output across simulation stages. This white paper highlights the importance of adopting a defect mitigation strategy during design and manufacturing to ensure a component's structural integrity and safety.

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Contents

Introduction

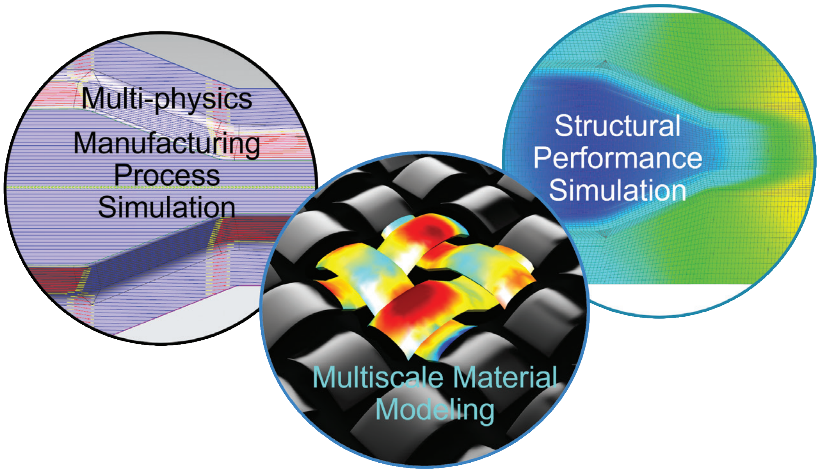
This white paper provides an overview of the Simcenter capabilities for simulating the RTM technology for composite manufacturing and demonstrates them with an automotive case study about a vehicle B-Pillar, a critical safety component in a car.

RTM is one of the key manufacturing technologies used for composite structures. The streamlined workflow includes key manufacturing stages present in RTM manufacturing: draping (placing a textile reinforcement onto a mold) and infusion, where a resin impregnates the dry reinforcement; curing/demolding, where resin solidifies, and residual stresses are developed that cause the composite part to have spring-in and warpage after demolding.[1]

A multiscale multi-physics workflow has been proposed to address composite manufacturing simulation.[2] This workflow aims to significantly reduce and even eliminate defects in the design and manufacturing stages of the composite parts manufactured using RTM.

The solution leverages a combination of high-fidelity user-friendly computer-aided design (CAD) and CAE tools offered by Siemens Digital Industries Software:

- Simcenter 3D is a unified, scalable, open and extensible environment for geometry-based (3D) CAE simulation, enabling validation and optimization of products[3]
- Simcenter STAR-CCM+™ software is a multi-physics computational fluid dynamics (CFD) software for simulating products operating under real-world conditions[4]
- Simcenter 3D Laminate Composite combined with NX™ Composites software speeds up the design and simulation of laminate composite materials with a seamless connection to composites design, accurate solvers and adequate postprocessing[5]



Siemens offers a multiscale multi-physics workflow to address composite manufacturing simulation. This workflow aims to significantly reduce and even eliminate bottlenecks in the design, testing and validation of the composite parts manufactured using RTM.

Composites in automotive: challenge, solution and impact

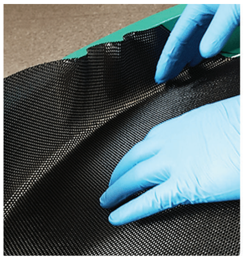
Composites manufacturing challenges

The automotive industry aims to manufacture a lighter car with a smaller environmental impact, which still has the properties needed to make them durable and safe. Advanced materials, such as composites, may be part of the answer since they can offer a combination of mechanical properties and weight reduction that helps to achieve this goal.

The primary challenge in carbon fiber composites manufacturing lies in its complexity, which differs significantly from the straightforward processes of metal stamping and plastic injection molding. Designing, simulating and producing carbon fiber composites is not a straightforward task. It involves dealing with a multitude of variables, each requiring careful anticipation, measurement and control.[6]

For composite materials to routinely replace heavier materials, it is essential to have production processes that meet the needs of the industrial product manufacturers. This includes the following elements:

- Efficient data flows from design to manufacturing
- Full control of how geometric shape, material and processes drive important engineering decisions that change the design in ways that can affect part performance
- A consistency in manufacturing operations that minimize variability and reduce quality issues in production



Inefficient data flow increases time-to-market

Challenge to make decisions based on shape, material and process

Lack of common methods result in low rate and quality

Using the NX Composites digital twin solves key manufacturing challenges and enables efficient integration of manufacturing influences in the composite product design.

Siemens digital twin solves key composite manufacturing challenges

Experimentally driven approaches are inefficient: designing, manufacturing and testing a part or developing and certifying new materials is a long and expensive process. CAE tools can play a key role in enabling this by allowing you to simulate and optimize the manufacturing processes and to predict the quality of the resulting pieces under given process conditions.[7] Such a material manufacturing digital twin (figure 1) can help industrial product manufacturers to reduce design and manufacturing costs and time-to-market as less design iterations are necessary.

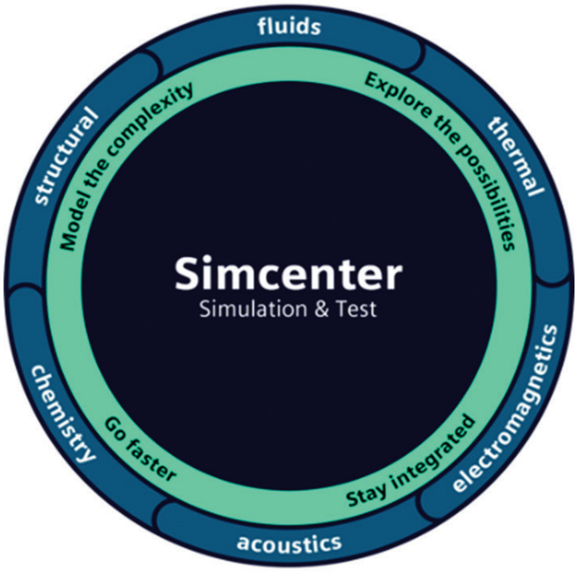


Figure 1. Simcenter simulation and test portfolio.

Siemens offers a wide range of tools, extensive data sets and advanced simulation capabilities. To maximize industrial value, we are committed to streamlining these resources for user-friendly access and operation. We see the adoption of a digital twin and systematic streamlined approach as a significant customer opportunity. Siemens is working on enabling customers to fully leverage digital twin technology for their industrial needs. Breaking down the manual process into a digital, multistage workflow solution also offers the potential step-by-step validation of results in a more controlled way using available measurement data or data available in the literature.

B-Pillar use case

The B-Pillar is a critical component in the automotive industry that connects the roof to the floor of the car, providing structural integrity. It plays a crucial role in overall dynamics and the safety of the vehicle. A composite B-Pillar made of carbon fiber fabric offers weight savings and the necessary strength and stiffness, improving a car's dynamics.

A woven reinforced carbon fiber composite B-Pillar was designed and manufactured with RTM. Chomarat C-WEAVE™ 285T 3K S woven sheets were cut and layered with a layup of [0°/60°/-60°/60°/0°] on both sides of the structure. The resin system is epoxy based Sicomin SR1710 with hardener SD8731.[8] Nominal thickness of the top and bottom laminates is 2 millimeters (mm) with a thickness of 0.4mm on each ply. Nominal fiber volume fraction within the ply is 40 percent.

The effect of manufacturing-induced defects (fabric shearing, residual deformations and residual stresses) is analyzed on the mode shapes of the B-Pillar. Understanding such effects is crucial for informed design decisions to prevent failure or damage.

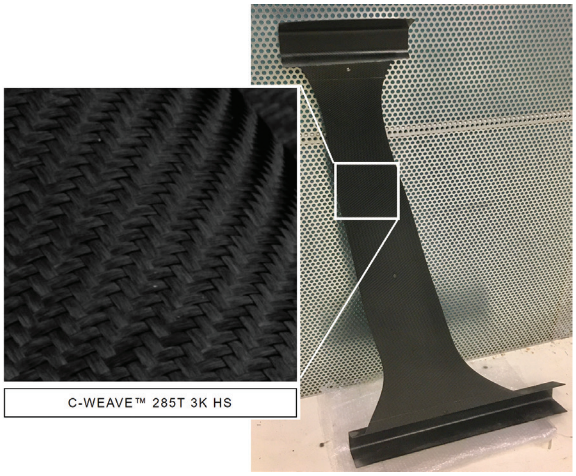


Figure 2. B-Pillar made of Chomarat C-WEAVE™ 285T 3K HS textile.

Streamlined simulation workflow for a composite B-Pillar

A streamlined simulation workflow is used on the example of RTM-manufactured composite B-Pillar, connecting composite manufacturing simulations with the performance of the part (figure 3). This workflow includes kinematic draping simulation, infusion simulation, thermomechanical curing analysis and modal analysis. The individual blocks will be explained in detail in the sections below.

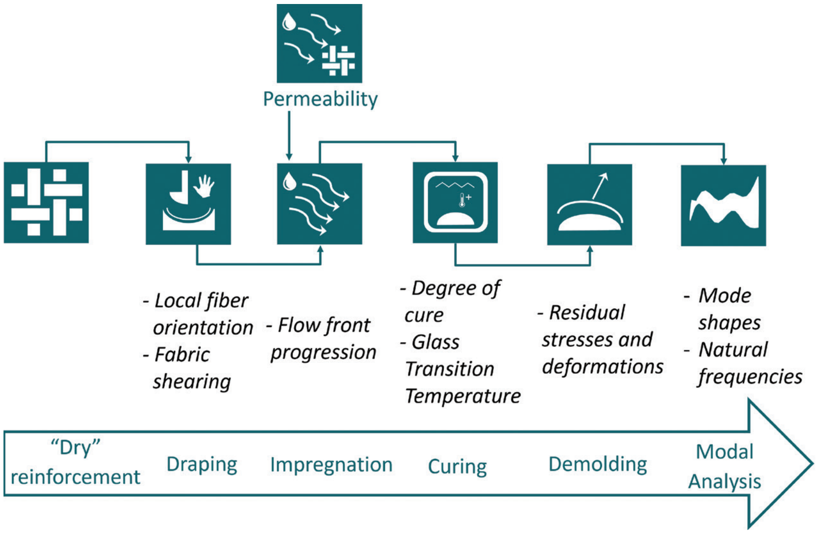


Figure 3. Illustration of the streamlined simulation workflow for composites manufacturing.

Kinematic draping simulations are used to determine local fiber orientations and assess manufacturability. These orientations serve as input for infusion simulation to compute flow front progression during RTM process and thermomechanical curing simulation to compute degree of cure and residual stresses and deformations at the end of the curing cycle. The last step in the proposed workflow is modal analyses that consider residual factors and local fiber orientation to compute natural frequencies and mode shapes of the part. The study explores different draping scenarios, curing cycles and their impact on residual stresses, deformations and mode shapes. This proposed streamlined manufacturing workflow reduces the time-consuming manual engineering work of synchronizing input/output across all simulation stages, enabling faster optimization of product designs for better performance.

Draping simulation

Draping woven materials on a mold involves laying out woven fabric sheets in a specific pattern or orientation to create a composite part. Several approaches exist to simulate such draping process. Simcenter 3D Laminate Composites offers a widely used kinematic approach, computing local fiber orientation based on the mold geometry, rosette point and draping strategy. The woven solver computes fiber orientation for cloth woven with two sets of fibers at an angle to each other. As fibers are assumed non-stretchable, the angular change produces shear distortion. Figure 4 shows a shear angle distortion on a piece of fabric with a 90-degree weft fiber angle. The warp lengths[1] and weft fibers[2] do not change, but the yarn angle[3] in between does change. The shear angle is the difference between the original yarn angle and the distorted yarn angle.

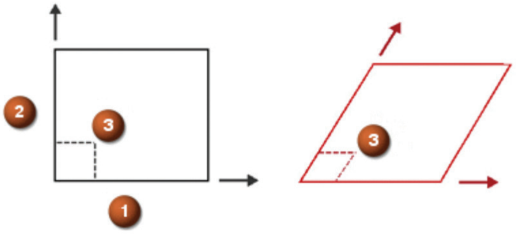


Figure 4. Schematic representation of the shear.

Quantification based on simulation allows identifying potential issues: if the shear angle becomes too large, the ply begins to wrinkle. There are elements with a large shear angle shown in red color in figure 5 for two draping cases, referred to as draping case 1 and draping case 2.

Such simulation-based quantification provides an assessment of the manufacturability of the part. Areas with a shearing problem can be addressed by taking measures at the design stage.

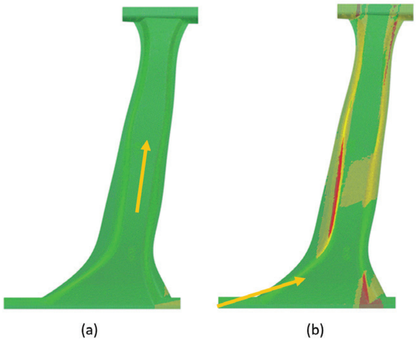


Figure 5. Visualization of the shear angle distortion in the ply 1 – 0 degree ply of the B-Pillar (yellow arrow indicates the draping direction and the location of the rosette point): (a) draping case 1, (b) draping case 2.

Permeability computation

An important parameter for the infusion simulation is the nominal permeability: the ability of a fluid (for example, epoxy resin) to flow through a fibrous reinforcement when subject to an external force (pressure). An automated workflow for saturated permeability (steady-state permeability when the reinforcement is fully saturated with a test liquid and flow is in the steady state) computation has been implemented as part of Simcenter 3D (figure 6).[9]

Validation of the permeability computation for the B-Pillar was done using micro-CT-based numerical validation. The results[9] show where small samples were cut out from various parts of the B-pillar component, focusing on areas with minimal and maximal shear angle. Acquired micro-CT images were segmented into yarn and resin regions. Using Simcenter 3D, finite element models were set up to calculate the permeability of each specimen. These results were compared with a local permeability map, analytically calculated based on shear angle. The local permeability map was verified against experimental data of the flow front progression in the B-Pillar.[7]

Infusion simulation

Using Simcenter STAR-CCM+ for infusion simulation can help composite engineers to simulate and optimize the resin flow during RTM. It can provide insights into the filling pattern, process-induced defects such as void formation and suggest process improvements to reduce the manufacturing cycle time and cost.

Using Simcenter STAR-CCM+ offers a general CFD solver approach, solving Navier-Stokes equations. This assumes the fluid is incompressible and preserves a lot of the physics of the flow in the solution sequence, so physical phenomena can be predicted more accurately.

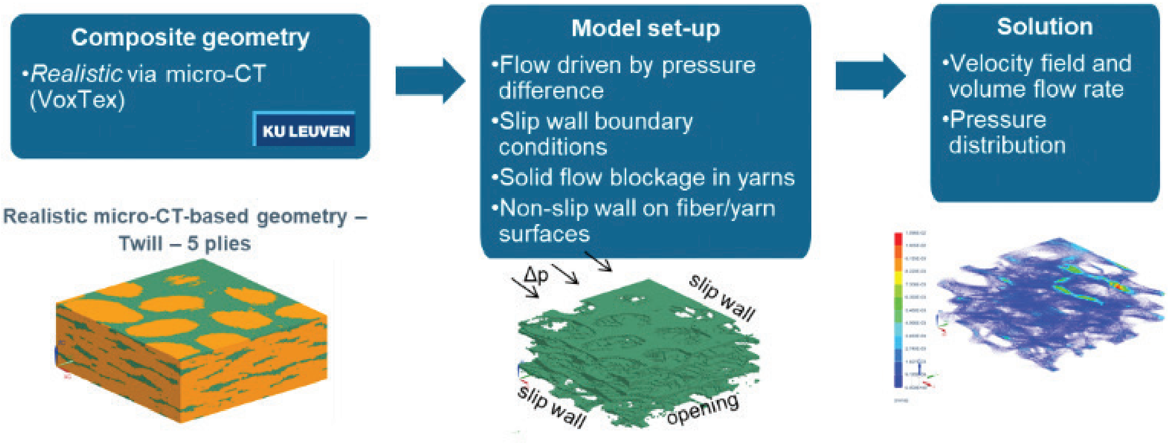


Figure 6. Permeability computation workflow (shown in the example of Chomarat C-WEAVE™ 285T 3K HS).

The infusion simulation workflow involves the following steps: execution of the draping simulation workflow; definition of the local permeability map based on the local fiber orientation and nominal permeability value of non-sheared fabric (using Demaria et al.[10] analytical formulation); definition of the infusion channels and flow boundary conditions; definition of the solution of fluid mechanics to predict the resin flow in Simcenter STAR-CCM+ and postprocessing of the simulation results to analyze the flow front progression.

Using Simcenter STAR-CCM+ allows you to model infusion and curing processes in parallel. This is especially relevant for fast-curing resins that start to harden during the infusion process. However, for the B-Pillar under consideration, the part was first fully impregnated before it was cured. Therefore, in this workflow, infusion is decoupled from the curing workflow.

Figure 7 illustrates a good agreement between the simulations and the experimental results (obtained via optical Fiber Bragg Gratings (FBGs)) of the flow front progression and supports the validity of the local permeability map.[7]

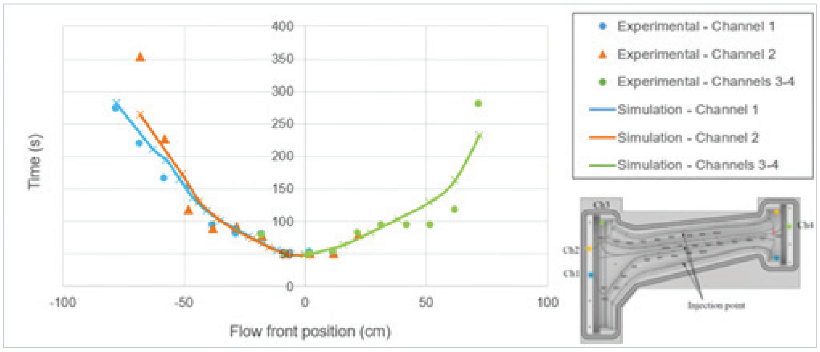


Figure 7. Time at which the flow front passes through each sensor location (symbols are experimental data, continuous lines are simulation results); on the right bottom corner, a scheme shows the sensor locations.

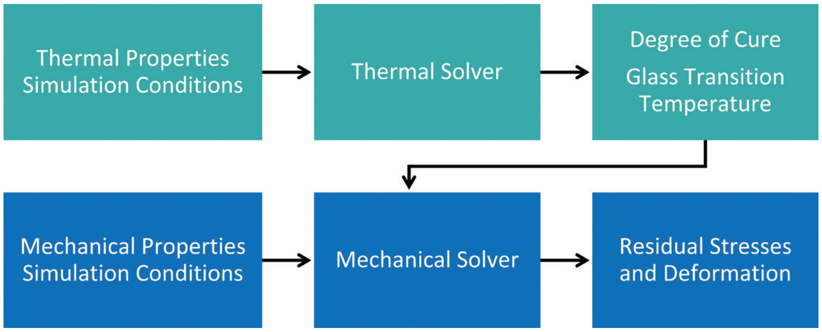


Figure 8. Illustration of the workflow for curing simulation and computation of residual stresses/deformations.

Curing simulation

Curing simulations for thermoset composites involve using numerical methods to simulate the curing or hardening of the resin matrix that occurs when it is heated to a specific temperature for a certain amount of time. These simulations can be used to predict the degree of cure, temperature distribution, residual stresses and residual deformations in the composite material during and after the curing process. With Simcenter 3D, curing predictions (thermal and mechanical) can be performed as a two-step solution, by sequentially coupling a thermal and a mechanical model, as illustrated by the workflow shown in figure 8.

A closed two-sided mold made of steel was generated to completely cover the part from all the sides. Kamal and Sourour curing kinetic model[11] was used in this study to predict the degree of cure. In the curing simulations, we replaced Sicomin SR1710 with HexFlow RTM6 resin due to the unavailability of required input data. The cure kinetics material properties of HexFlow RTM6 resin are available in the literature.[12] Two thermal cycles were considered with the maximum temperature of 180 degrees Celsius (C°) and 143 C° respectively. In both cases, the temperature field was applied on top of the mold (simulating the heat plate), allowing gradual distribution of the temperature through the thickness of the part. The first cycle led to a complete cure and the second to a partial cure with the maximum degree of cure of ~0.7 (figure 9).

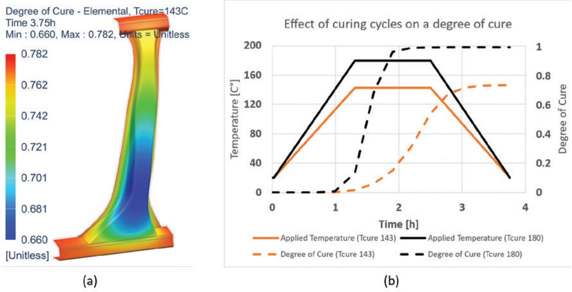


Figure 9. (a) Degree of cure distribution for the curing cycle with maximum applied temperature of 143 C°; (b) effect of curing cycles on degree of cure.

The evolution of the degree of cure and glass transition temperature as a function of time were then mapped to the mechanical solver. The mechanical solution has two distinctive subcases:

- Curing subcase, where the pressure field of 5.8 Bar is defined and applied on the upper surface of the mold
- Demolding subcase, where the pressure was reduced to zero and the mold was detached from the part

The effect of the curing cycles on the residual stresses is shown in figure 10.

The B-Pillar with a partial degree of cure has a lower stiffness and therefore smaller residual stress concentrations when compared with a fully cured B-Pillar. To optimize the set of manufacturing parameters one should maximize the degree of cure by minimizing the residual stresses and deformations in the part.

The effect of draping on the residual stresses and deformations for the cure cycle of 180 °C is shown in figure 10bc and 11, respectively.

Draping case 2 has a notable impact on the distribution of stress, especially in areas characterized by high shear angles. This effect and its magnitude vary depending on the ply and the criticality of the area being considered. For example, in the first ply, the stress concentration originally present in the upper part (as seen in figure 10b) was redistributed, resulting in a different area of stress concentration with a magnitude that is 20 percent higher, as evident in the lower part of the B-Pillar, particularly in regions with high curvature (figure 10c). Residual deformations mainly occurred at the tails of the B-Pillar, which is an expected spring-in behavior. For draping case 2, the deformations were found with a more pronounced torsion, however the magnitude of deformation is only 0.3 percent higher than in draping case 1.

In all cases, it was observed that residual stresses remained below the ply strength, which for this material is approximately 450 Megapascal (MPa).

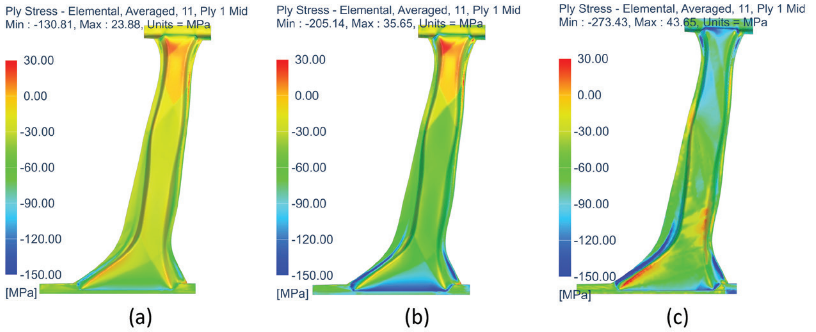


Figure 10. Residual stresses in the fiber direction (ply 1 – 0° ply): (a) 143 C° curing cycle, draping case 1; (b) 180 C° curing cycle, draping case 1; (c) 180 C° curing cycle, draping case 2.

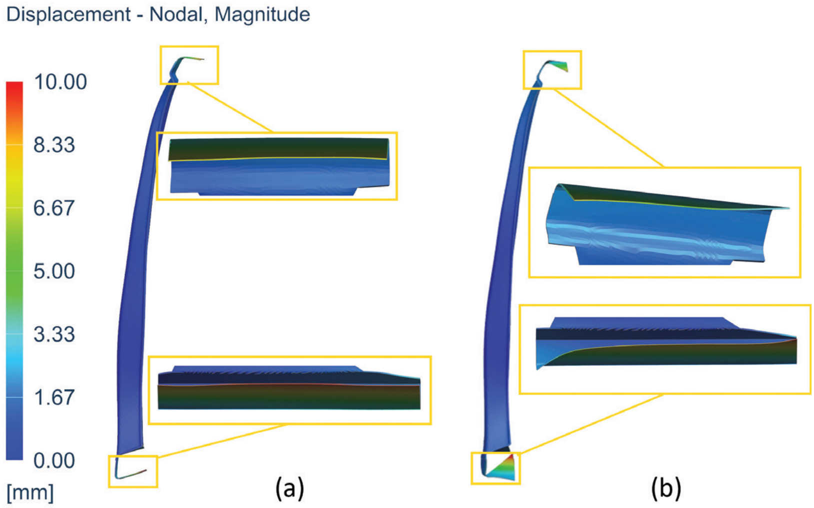


Figure 11. Residual deformations for the cure cycle of 180 C°: (a) draping case 1, (b) draping case 2. (The deformations visualization in the image is scaled with a factor of 5 percent to highlight the difference).

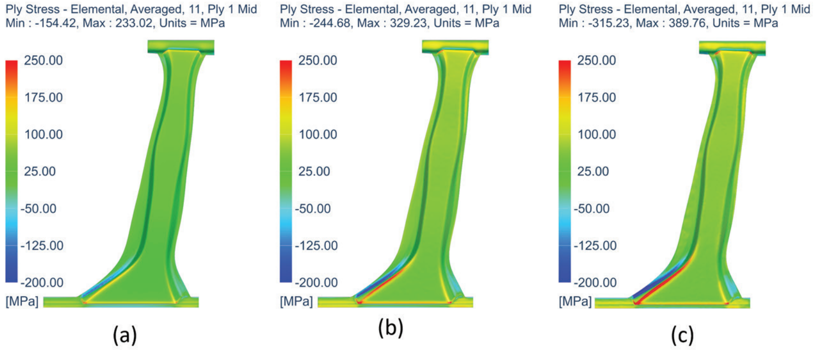


Figure 12. Stresses in the fiber direction (ply 1 – 0° ply) in the end of the curing cycle before demolding: (a) 143 C° curing cycle, draping case 1; (b) 180 C° curing cycle, draping case 1; (c) 180 C° curing cycle, draping case 2.

However, it’s worth noting that in some plies stress levels approached the strength values during the cycle prior to demolding (figure 12).

This can potentially trigger damage initiation and propagation within the laminate. To fully comprehend the impact, nonlinear analyses incorporating material damage need to be conducted. This is important to designers, highlighting the need for varying degrees of reinforcement in areas displaying high residual stresses and deformations.

Curing simulations are key to optimizing the curing process, predicting the ideal temperature and time required to achieve a desired degree of cure and minimize residual stresses and deformations. One can identify upfront potential defects/weaknesses and apply updates to reducing the risk of failure in the final product.

Modal analysis

The final step in this multiscale and multi-physics workflow of composite manufacturing simulation is closing the loop with performance simulation. Functional performance includes the product stiffness, strength, impact, durability, noise and vibration. A numerical modal analysis was performed on the manufactured composite B-Pillar part. Natural mode shapes (for example, shapes of natural vibration under excitation) provide insight into dynamic behavior of the part. By studying mode shapes, engineers can identify potential weak points, stress concentrations or areas prone to failure. Tuning the design can alter the mode shapes and corresponding resonance frequencies, which is an important instrument for engineers to understand and optimize the part and assembly behavior.

Eigenvalues and eigenvectors were computed in Simcenter 3D with an iterative Lanczos algorithm. Different boundary conditions (BC) with free and clamped tails were analyzed and their modes shapes were investigated with two draping cases and two curing cycles. Residual stresses were mapped to the plies and initial node positions were updated according to the stresses and deformation values at the end of the curing cycle. Additionally, it was also necessary to update the matrix stiffness according to the final degree of cure:

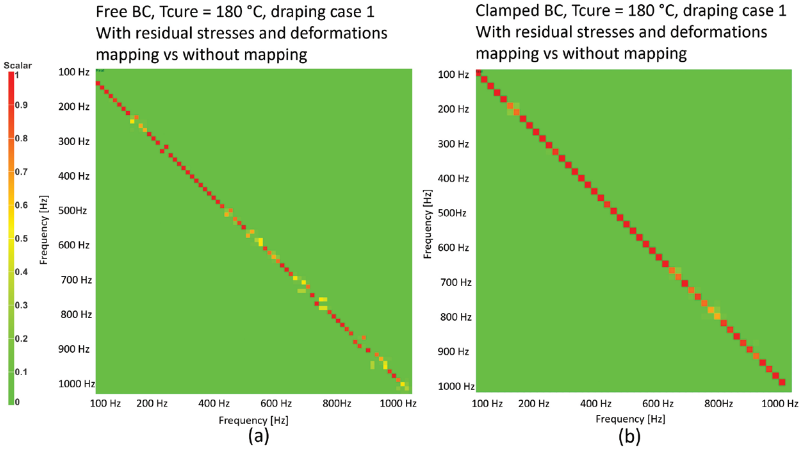
$$E(\alpha)=(1-\alpha)E_{uncured}+\alpha E_{fully\ cured},$$

where α – is the degree of cure, $E_{uncured}$ is equal to the stiffness in the liquid state of the epoxy and Ecured to the glassy state.

Modal assurance criterion (MAC) analysis was used to compare mode shapes between different cases. It is a useful tool that can indicate the similarity of two mode shapes.

The influence of various curing cycles on mode shapes is minimal, as illustrated in figure 13a.

In contrast, the impact of draping is more substantial, as shown in figure 13b.



(a)

(b)

Figure 13. MAC: (a) effect of the curing cycle on the mode shapes, (b) effect of draping on the mode shapes.

Altering the draping input leads to significant changes in the B-Pillar's deformation and stresses after demolding, resulting in larger variations in mode shapes, with 73 percent of them having MAC values below 0.8 (meaning that 73 percent of mode shapes being compared are different by more than 20 percent).

When the tails are clamped, there is improved correlation in comparison to using free boundary conditions. This is because the most relevant residual deformations are concentrated in the tail regions of the B-Pillar (figure 14).

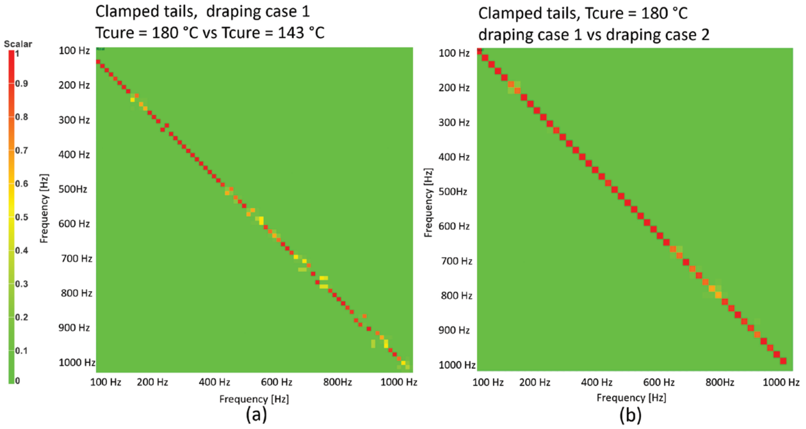


Figure 14. MAC: effect of the residual deformations and stresses on the mode shapes; (a) free BC; (b) clamped BC.

Results

A streamlined simulation workflow is proposed that links composite manufacturing simulations with the part performance using the example of RTM manufactured composite B-Pillar. The kinematic draping simulation is executed first to obtain local fiber orientations through textile shearing and to assess the manufacturability of the part. Two draping scenarios are investigated to achieve different shear angles: draping case 1 with lower shear angles and draping case 2 with higher shear angles. Local fiber orientation is then served as an input in a thermo-mechanical curing analysis, where thermal data, such as the degree of cure and glass transition temperatures, is chained to the mechanical domain.

This connection allows the computation of residual stresses and deformations that occur in the part due to the mismatch in the thermal expansion coefficients between fibers and the epoxy and during the demolding step of the curing analysis. The examination of different curing cycles, including a 20 percent reduction in temperature from 180°C to 143°C, revealed a substantial 30 percent decrease in the degree of cure from 1.0 to 0.7. Moreover, draping case 2 characterized by larger shear angles notably influenced the distribution and values of residual stresses, including a 20 percent increase in stress concentrations in the 0°-degree ply. Modal analyses were conducted to calculate the natural frequencies and mode shapes of the structure under varying boundary conditions while considering residual deformations, residual stresses and local fiber orientation. The influence of different curing cycles on mode shapes in relation to residual stresses and deformations was found to be negligible. However, it was observed that altering the draping input significantly impacted the post-demolding deformation behavior of the B-Pillar, particularly at its tails, resulting in a substantial difference in mode shapes. Although the influence of different curing cycles on mode shapes is small, conducting curing analysis in RTM composites is critical for several reasons. One of the primary reasons for conducting curing analysis is to assess its impact on stress distribution and stress values in the composite part. The curing process introduced residual stresses and temperature gradients within the material. These residual stresses lead to deformation, warping or even the initiation of microcracks or delamination, which can compromise the structural integrity of the component over time. By analyzing the curing process, manufacturers can identify regions of high stress concentration and take corrective measures to minimize these issues. Furthermore, conducting curing analyses is essential for the purpose of minimizing curing durations and temperatures without compromising the performance of the component. This not only conserves energy but also reduces manufacturing time.

Additionally, saturated permeability of a non-sheared fabric was calculated and mapped to the finite element method (FEM) model of the B-Pillar based on the local fiber orientation of the fibers. These served as an input to the infusion simulation where the flow front progression was simulated. The results were compared with the available experimental data, obtained via optical FBGs.

Outlook

This entire process can be captured in HEEDS™ software,[13] a process integration and design space exploration tool that supports optimizing process and product parameters. This enables you to find feasible and optimal design realizations with improved efficiency, reduced costs and higher quality processes and products. By optimizing processes simultaneously, the manufacturing and performance aspects, smaller safety factors can be used, which will allow you to reduce component weight. In addition, the productivity will increase, decreasing the overall cost as the simulation workflow will minimize the trial-and-error approach.

Additionally, connecting composite manufacturing workflow with open innovation platforms (OIPs), such as OpenModel, uses automation to offer value beyond just an efficient workflow. It can offer access to a wider range of expertise, collaboration and knowledge sharing, as well as accelerating product development. This means working faster together in an industrial value chain and reducing costs and risk for research and development (R&D).

Simcenter, NX and HEEDS are part of the Siemens Xcelerator business platform of software, hardware and services.

OpenModel – Integrated open access materials modeling innovation platform for Europe

To help European industrial product manufacturers to develop products using composite materials, Siemens Digital Industries Software is participating in the OpenModel project where the composites modeling and simulation workflow outlined in this paper is coupled with the OpenModel OIP platform, providing efficient data flow between OIP and Siemens tools. The cloud-based platform will help European manufacturers standardize and automate the process to build and execute complex materials modeling and simulation workflows.

Conclusion

The composite manufacturing simulation workflow consists of many steps using multiple software tools, pre/postprocessing techniques and scripts for data conversion. Making it a seamless connection is challenging due to differences in file formats, modeling techniques and user interfaces, thus adding extra complexity to the full workflow execution. The Siemens solution makes the full workflow available as one piece.

Customer value

The proposed continuous chain of manufacturing steps contributes to significant time savings and helps engineers refine the design of specific products for optimal performance. When compared to using standalone tools, this streamlined process provides several distinct advantages for customers:

- **Efficiency:** The streamlined process reduces the need for manual data transfer and translation between different tools. This minimizes the risk of errors and the time spent on data preparation, allowing engineers to focus more on design and analysis
- **Time-to-market:** By automating the data flow and computations, the streamlined process accelerates the time it takes to obtain valuable insights.

Engineers can quickly iterate design options, reducing development cycles and time-to-market

- **Optimization opportunities:** With the ability to assess manufacturability, performance and other critical aspects in a coherent manner, engineers can identify optimization opportunities that might be missed when using standalone tools. This can lead to superior product designs
- **Cost savings:** Streamlining the workflow can lead to cost savings by reducing the need for multiple software licenses and the associated training and support costs. It also minimizes the risk of costly errors that can occur when using disparate tools.

Acknowledgments

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