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COMPOSITE FABRIC MANUFACTURING STUDIES BY SIMULATION AND EXPERIMENT

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Abstract

The tooling for fabricating continuous fiber composite components is affected by the geometry of the flat patch and forming process. Therefore, simulation tools are used to try out different process setups with initial design. The draping simulation can identify areas of wrinkling and stretching, and predict the fiber orientation and thickness distribution during the manufacturing of parts. This type of analysis helps to reduce the experimental tryouts for eventual part manufacturing. This paper presents studies on two of such continuous fabric reinforced composite parts with simulation and experimental trials, the layup of multiple plies of fabric composite prepreg are 12 layers and 24 layers respectively. Two different approaches are proposed for the simulation of a large and complicated geometric part, and different simulation trials on the relatively smaller but more complicated parts. The composite material draping simulation method is based on finite element analysis to calculate the bending and in-plane shearing effects with de-coupled stiffness values. Experimental trials indicated that the simulation analysis really helped eliminate possible wrinkles and excessive stretching, and the simulation method is a good tool in manufacturing the continuous fabric composite components.

Introduction

Laminated composites with multi-layered reinforcements have become increasingly popular due to outstanding success in aircraft industry [1, 2], and they have been rapidly adopted in automotive industry for weight saving of some auto-components. Nevertheless the use of these laminated composites is restricted by manufacturing complexities, and some unexpected local mechanical properties due to some defects induced during the manufacturing process. When the number of layers for the laminated composites is high, the high labor requirement in manual lay up of plies can be expensive in the try-outs, and for automotive industry, automation of the manufacturing of these laminated composites components could face quite some challenges in the setup without carefully detailed try-outs to identify possible issues and find ways to resolve them. Simulation of the manufacturing processes with a well-developed software thus becomes a necessary step to reduce the number of try-out cycles during the development phase of a product.

The work presented was performed as a subtask by the USCAR consortium of Ford, GM and FCA, initiated the Validation of Material Models (VMM) project. The objective of this four-year, $7 million U.S. DOE and USAMP Cooperative Agreement project is to validate and assess the ability of physics-based material models to predict crash performance of primary load-carrying carbon fiber composite automotive structures. Models evaluated include Automotive Composites Consortium/USAMP-developed models from the University of Michigan (UM) and Northwestern University (NWU), as well as four major commercial crash codes: PAM-CRASH, LS-DYNA, RADIOSS, and ABAQUS. Predictions are being compared to experimental results from quasi-static testing and dynamic crash testing of a lightweight carbon fiber composite front bumper and crush can (FBCC) system which was selected for demonstration via design, analysis, fabrication, and crash testing. The successful validation of these crash models will facilitate improved design of lightweight carbon fiber composites in automotive structures for significant mass savings. The primary project goal was to assess the technical readiness of composite crash simulation through efforts of the virtual design of a front bumper crush can (FBCC) system and the validation of its finite element-based performance prediction. The FBCC system needs to be first built with expected quality before validation tests both with performance simulations and with experiments under a series of high and low speed tests.

ESI was tasked to investigate the design of the preforming and compression molded composite front bumper beam as well as the crush-can, with the objective to employ woven or 2D carbon fiber fabrics for the primary structure. This paper focuses on the manufacturing simulation methods, by using ESI's well-known software PAM-FORM, for the simulation of preforming process of the two components of FBCC, that is, the multi-layered composite front bumper and the crush-can as shown in Figure 1.

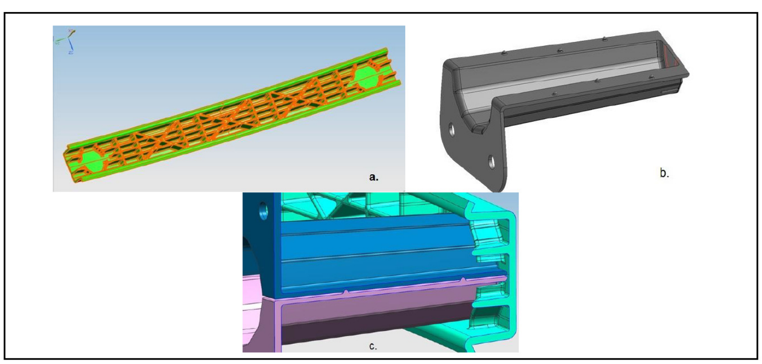

Figure 1. a. Carbon composite bumper, b. Half of crush-can and c. Connection between bumper and crush-can

Both the front composite bumper and the crush-can are manufactured with multiple layers of carbon fabric prepregs, the following orientations are designed for the symmetric layups:

Bumper: $[0/45/-45/90/90/-45/45/0/0/45/-45/90]_s$

Crush-can: $[0/45/-45/90/45/0]_s$

Following the draping process of the prepreg plies, both the front composite bumper and the crush-can will be molded additionally employing SMC material by a compression molding process to form the ribs and rear mounting plate respectively.

Bumper Preforming Simulations

The bumper is designed to have 24 layers of woven carbon fiber prepreg with layup as listed above. The upper and lower die shapes for preforming the carbon composite bumper are initially designed as shown in Figure 2. From the view shown in Figure 3, it can be seen that there is a sharp “V” shape in the upper die side, and the blank holders are designed to facilitate the draw of the prepreg plies into place. It is essential to simulate the manufacturability of the designs and identify any potential issues for the preforming process.

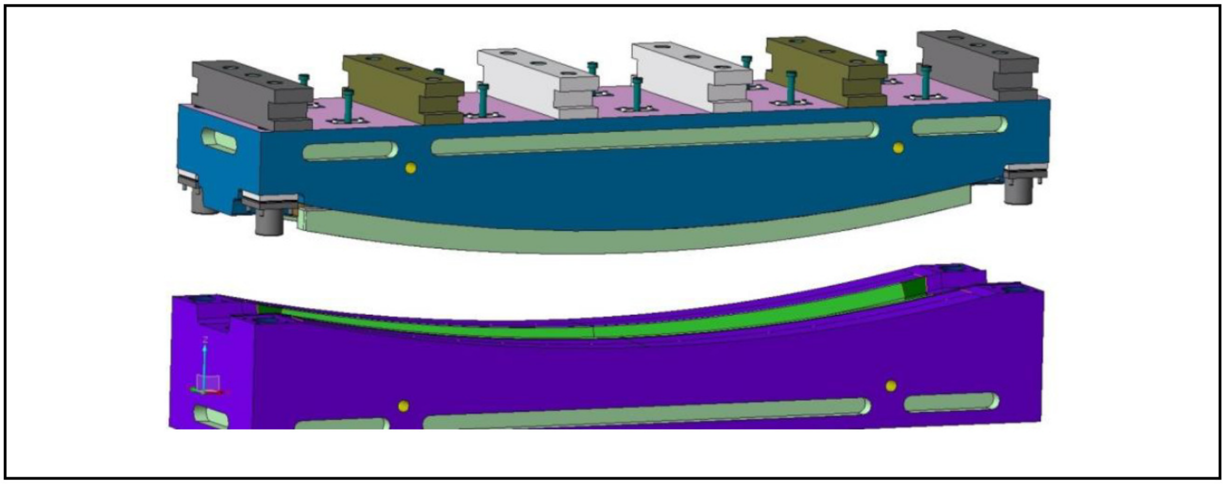

Figure 2. The upper and lower forming die halves for preforming of the carbon composites bumper

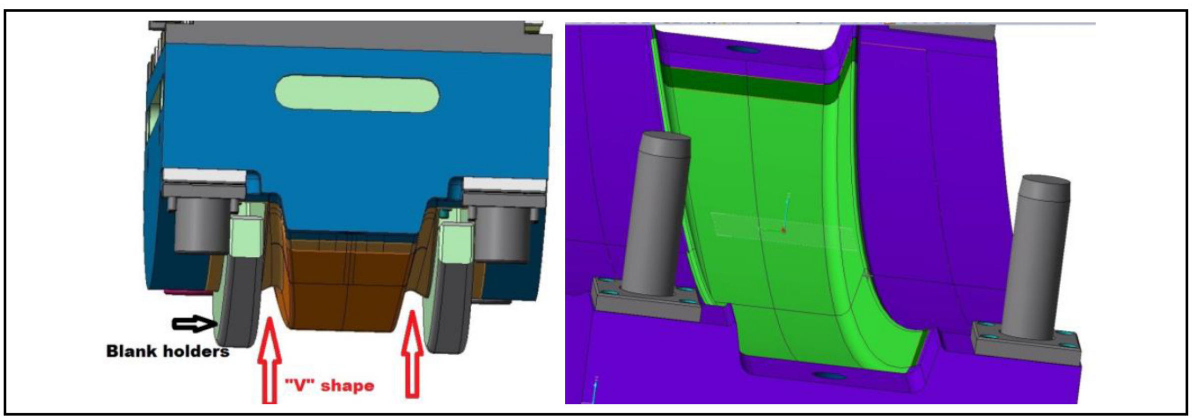

Figure 3. The upper and lower die halves for preforming of the carbon composites bumper in a different view

An initial simulation model was built by extracting the die surface and the punch surface from the bumper geometry as shown in Figure 4. In order to have a quick evaluation, the initial mesh model was based on a quarter of the whole bumper by making use of the symmetries in two planar directions, and just a single layer of the prepreg to see if there would be any issues, such as can be seen from Figure 4 that the prepreg blank would be pushed towards the blank holder side, and that, due to the “V” shape of the bumper design, the prepreg would pop up close to the blank holder, the “V” shape die surface geometry would also stretch the ply on the core side that makes the prepreg not easy to be drawn in the deep “V” valley. Realizing that the “V” shape as designed would be formed in the compression mold, a suggestion was made to modify the die design to have the “V” shape removed after this initial simulation as shown in the left graph of Figure 4.

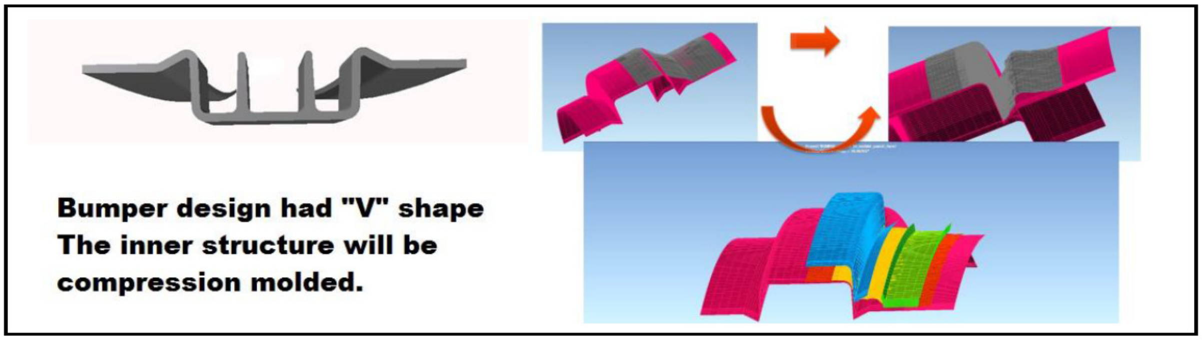

Figure 4. Initial quarter mesh model for simulation. The “V” shape would push the prepreg blank to the side

Simplification of the Model for Multiple Layers

In order to very quickly assess the formability of the design, a representative small section of the part was used to model the bumper behavior during the preforming process. This simplification approach for the model is made in order to conduct the simulation without losing the predictability of possible defects, and come up with helpful suggestions for the preforming manufacturing.

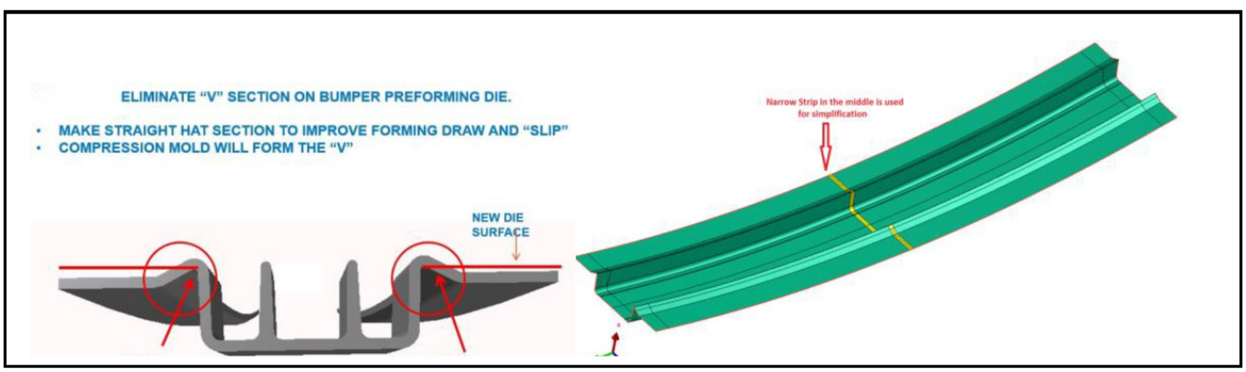

Figure 5. Left: Suggested change on the “V” shape, move it to the compression molds

Right: Schematic view for model simplification: use a narrow strip in the middle

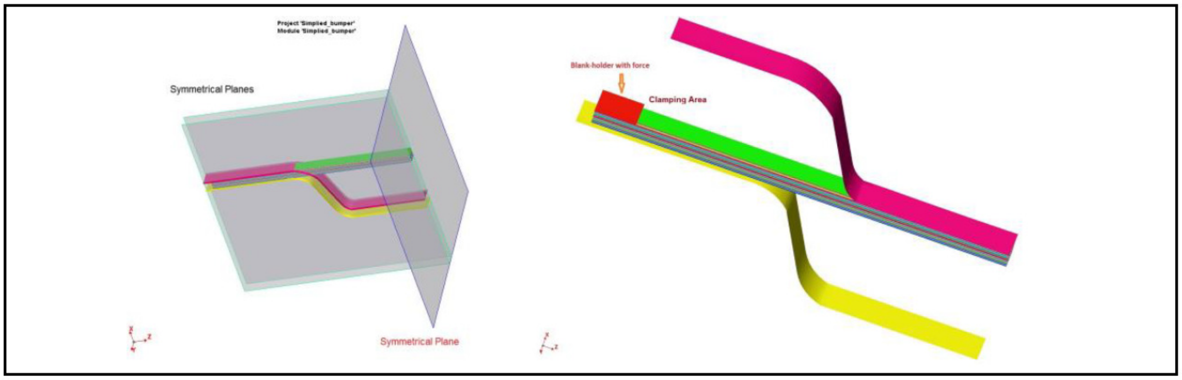

Figure 6. Left: Half of the middle strip with 24 layers is modeled with symmetrical planes defined

Right: The setup of the boundary conditions intended for clamping force and clamping area

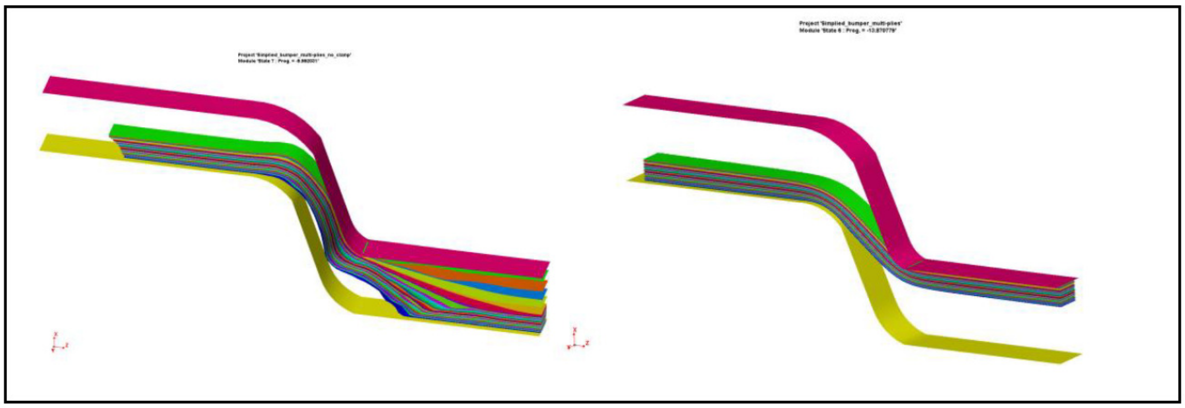

Figure 7. Left: Preforming without clamping would yield wrinkles and delamination during the process

Right: Preforming with a no slip condition in the clamping area would not push the plies into the cavity

The simplification idea is to take only a narrow strip in the middle of the bumper as shown in the right graph of Figure 5, and use the symmetrical X-Y plane in the middle to further reduce the strip into only an half, and other two X-Z planes in both sides of the strip to be one of the boundary conditions for the strip, and gravity stage can be turned on and off to see the effect of it on the draping. The upper forming die and lower forming die of the strip are modeled with surface strips as shown in the left of Figure 6 in red and yellow color, respectively. If no clamping on the multiple plies were used, the simulation could predict wrinkles and delamination during the preforming process, as shown in the left of Figure 7, whereas the other extreme is too tight clamping of the prepreg plies, that is, no slip condition at the end of the plies, the simulation showed that it would be making the preforming into the cavity impossible, shown in the right graph of Figure 7, as the strong stiffness of the multi-ply carbon composites would not deform further unless a huge punching force tried to break them.

The simulation model can then be setup to vary the clamping area and clamping force as the design variables for manufacturability. For example, if a small area of clamping is used and not enough clamping force to hold the carbon plies tight, the plies can be drawn in and slip out of the clamping area still forming wrinkles as shown in Figure 8. A large enough clamping area and holding force should be the ideal boundary condition for holding the plies with certain slippage yet not drawn out of the clamping area, and the eventual multiple plies can be draped into the right shape without yielding delamination and wrinkles, as shown in the right graph of Figure 9.

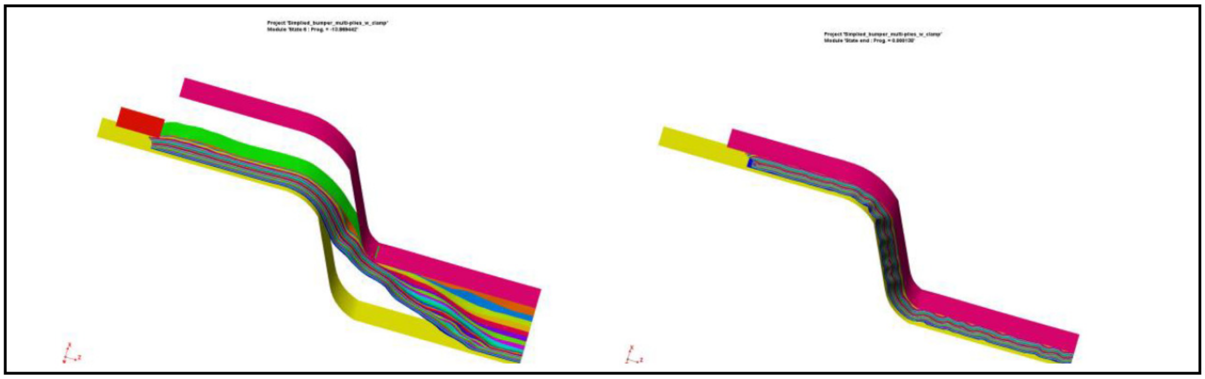

Figure 8. Left: Slippage out of the small clamping area due to draw-in during the preforming process; Right: Eventual preform with small clamping area, wrinkles are predicted

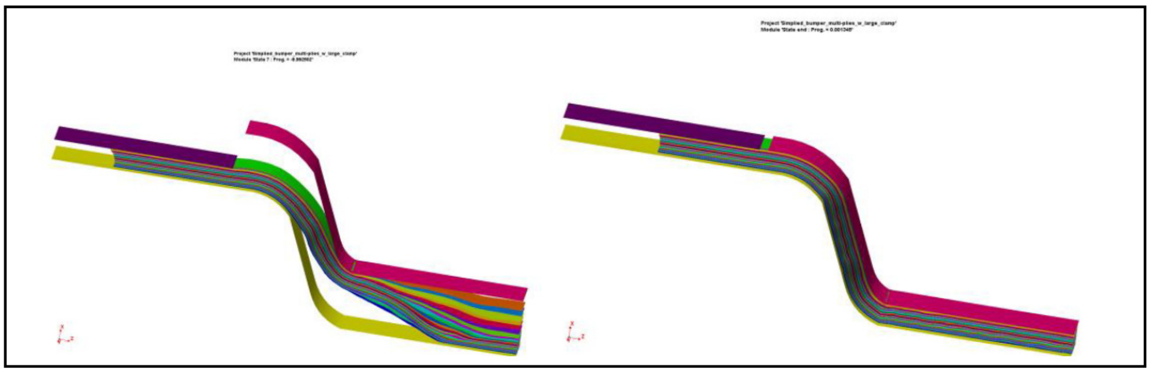

Figure 9. Left: Preforming with a large clamping area; Right: the end result of draping with a large clamping area

Crush-can Preforming Simulations

The crush-can assemblies consist of two identical halves due to symmetry, and it is designed to have 12 layers of woven carbon fiber prepreg with layup as listed in the introduction. The upper and lower forming die shapes for preforming the carbon composite bumper are initially designed as shown in Figure 10. As illustrated in the right image, there is a 22 degree angle set to accommodate the draping of two 90-degree bending ends of the preform which are considered difficult to form with the stepped semi-circular curved cavity shape.

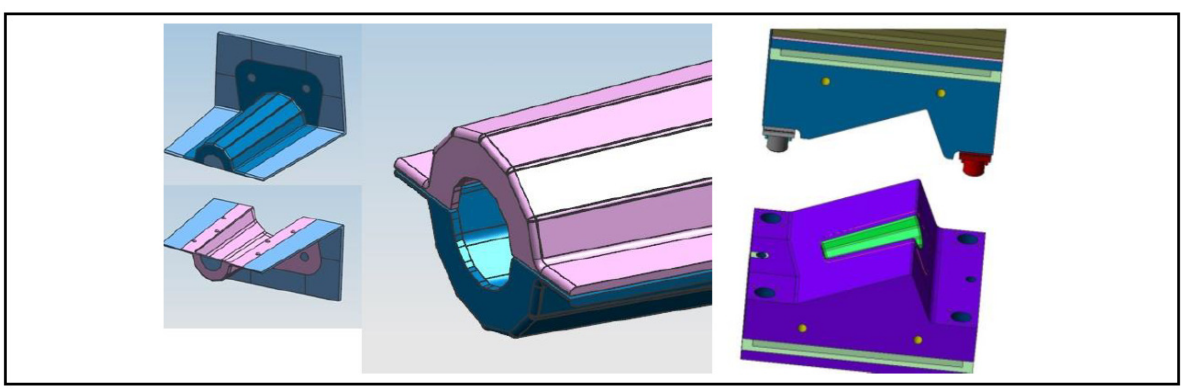

Figure 10. The designs of the laminated composite crush-can with two halves, and the die set for the preforming

It can be seen that the two end planes are not parallel, and the two 90-degree bending ends can definitely cause wrinkles and stretching. A pure geometry based draping analysis was first conducted by using FiberSim©, and subsequently using a single ply analysis with a default set of mechanical properties in Pam-Form. Quite some wrinkles and stretching were predicted as shown in the left image of Figure 11, if a single prepreg sheet were directly formed with the forming die set, therefore removing wrinkles and reducing stretch were the first targets of the initial analyses. The cutting scheme of the prepreg sheets was suggested by FiberSim©, as shown in the right image in Figure 11.

The suggested ply shape was used in the simulation of draping 12 layers of the prepreg with the orientations defined in the layup to predict any forming issues. The first stage of the simulation is about the gravity effect when the plies are laid on to the top of the lower mold. The positioning of the plies can be tricky due to the geometric model being modified in a different software, thus it needs some try-and-errors to place the cut plies in the right place. After the gravity stage, it is set to automatically start the simulation of the punching stage. Both the end of gravity stage result and the end of punching stage result are shown in Figure 12.

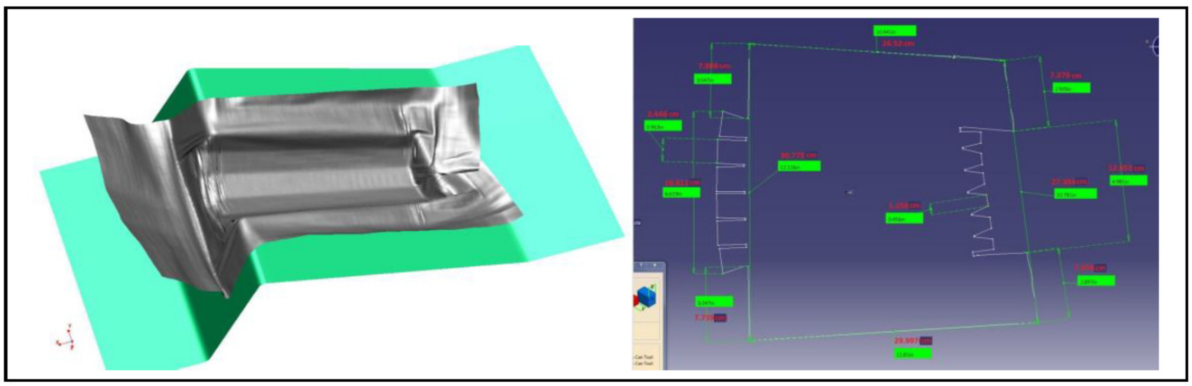

Figure 11. Left: Single sheet draping analysis results show quite some wrinkles and stretches in both ends;

Right: Suggested cutting diagram for reducing the wrinkles and stretches

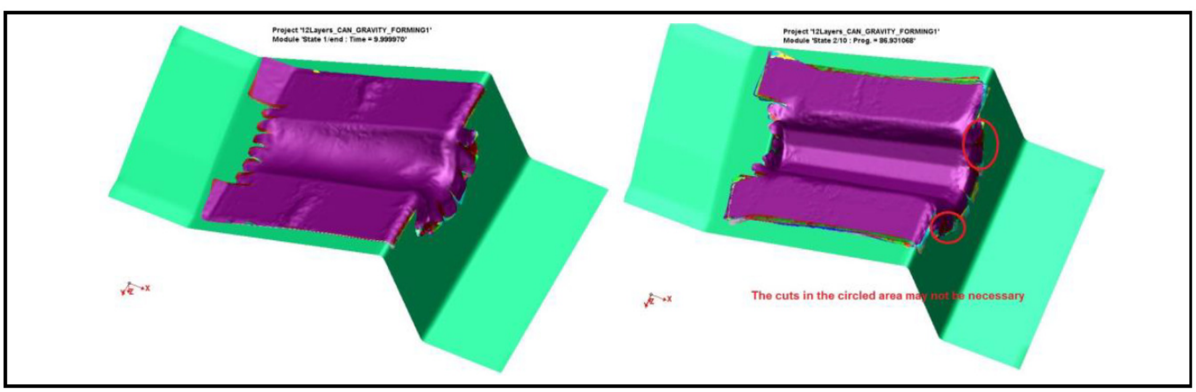

Figure 12. Left: The end result of simulated gravity stage; Right: The end result of simulated punching stage

It can be seen that 12 layers of the fabric plies do not line up when they are in the final shape of these stages, and there is little wrinkle in the final of the preforming as expected by the cutting scheme of the plies. However, there could be combined finger tabs in the flange of far right as the cuts there may not be necessary.

The other results from the simulation are good reference for manufacturing and for further simulation of the performance of the part in terms of the material properties. In particular, the final orientation results of each ply can strongly influence the mechanical properties for the crash performance. It is shown here in Figure 13 for just a couple of them to indicate how the orientations can look like in detail.

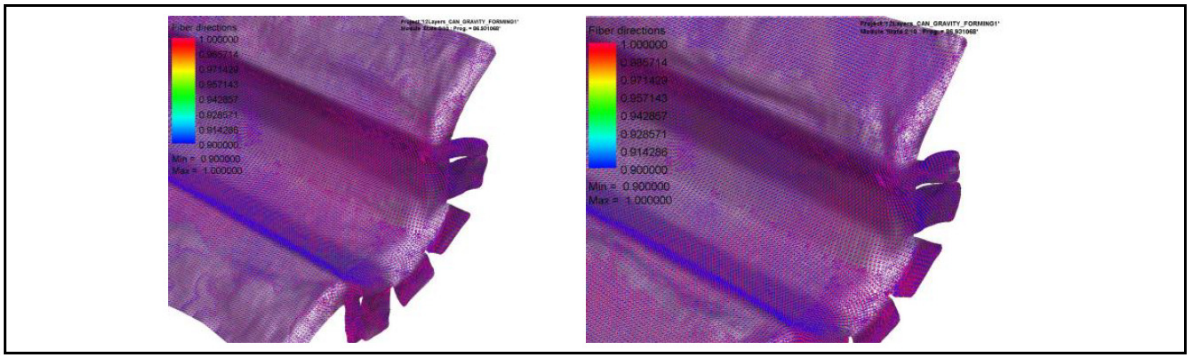

Figure 13. Left: The fiber orientation result of layer 2; Right: The fiber orientation result of layer 6

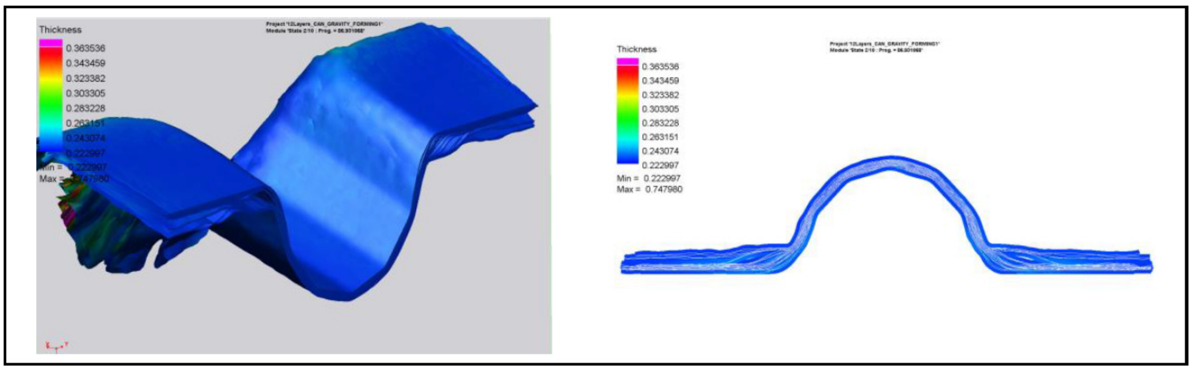

Figure 14. Left: Cross-sectional cut in 3D to show gaps between layers; Right: Cross-sectional cut in 2D plot

The simulation can also predict if there is any gap between the layers, and if so or deemed essential if it is possible to reduce it. A cross-sectional plot in a 2D cut with sliding bar can show this clearly as shown in Figure 14.

Manufacturing of the composite bumper and crush-can

The manufacturing process begins by first nesting the ply designs in their prescribed orientations in CSP’s Gerber Z1 cutting table computer. Figure 15 shows both the crush-can nested right and left sets of 12 prepreg pieces layout in a blank, and the bumper nested layout of the 24 prepregs according to their orientations. These labeled plies are then cut and kitted in the correct layup sequence as shown in Figure 16.

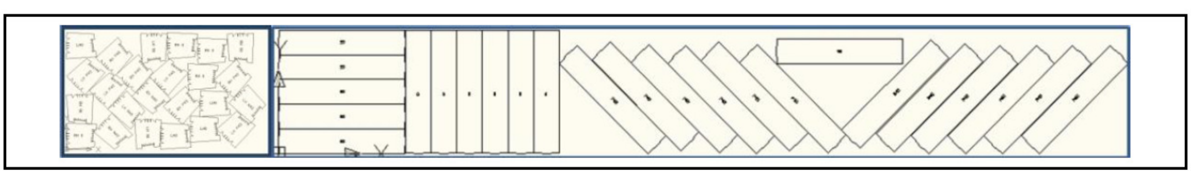

Figure 15. Left: Crush Can Nest (12 Plies each LH/RH); Right: Front Bumper (24 Plies)

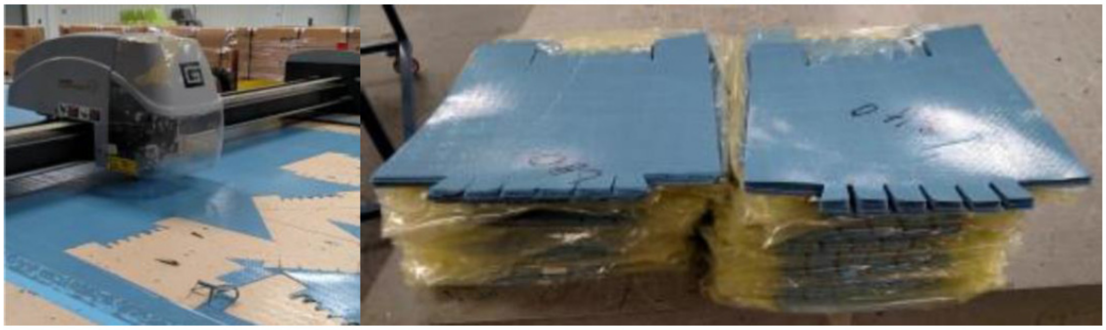

Figure 16. Crush-Cans: Left-Cutting; Right-Knitted

These 2D plies for Crush-can are manually preformed and formed to shape using aluminum preforming dies as shown in Figure 17. Presented in the left graph of Figure 18 are the forming dies for the crush-can, the compression mold set in the middle, and the right picture is the draping result of the crush-can with 12 layers of woven carbon prepregs. The rear flange tabs are extended and the cut tabs are reduced to four of them in the preforming, with considerations of the follow-up compression molding of chopped carbon fiber SMC.

Figure 17. Left: Crush-can Preforming Dies. Right: Preformed crush-can in the dies

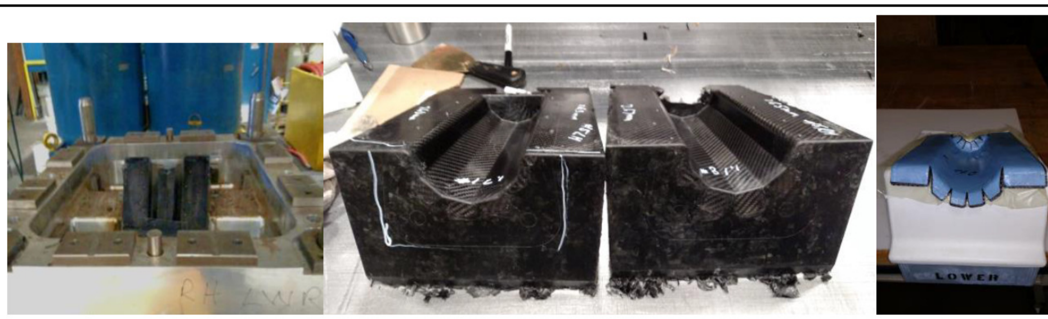

Figure 18. Left: Crush-can as molded; Middle: Compression mold set; Right: Crush-can after the draping

From the right image it can be seen that there is no wrinkles formed in both the front and the back of the crush –can part. This is the result of the extensive study with simulation tools.

Figure 19. Left: 2D Front Bumper Prepreg Plies; Right: 3D Front Bumper Preforming in the die

The front bumper is made by following the suggestion on the forming die change from the simulation results, to remove the “V” shape as shown in Figure 19, and the “V” shape is in the compression mold, so the designed shape of the front bumper is compression molded. Carbon fiber SMC is used to fill the core-side ribs of the front bumper as shown in Figure 20.

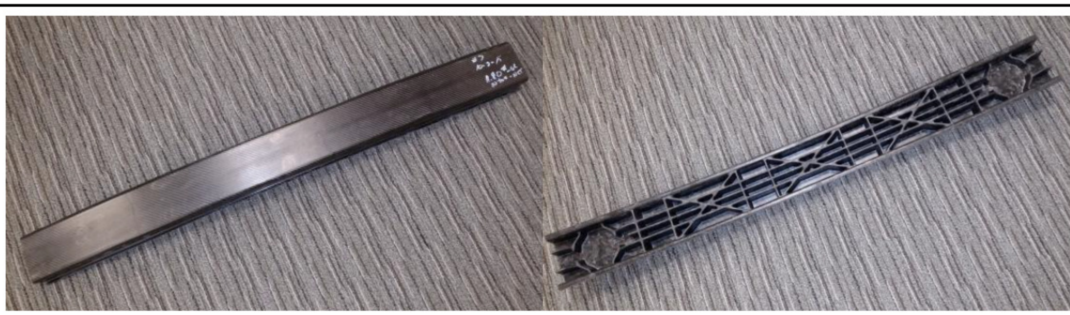

Figure 20. Left: Outside surface of the Front Bumper; Right: Inside structure of the Front Bumper

Summary and Next Steps

The simulation for manufacturing the woven carbon composite bumper with 24 layers of the fabric prepregs, and the 12 layers for the woven carbon composite crush-can has been presented in this paper. It is shown that the simulation tool for the preforming process helps the manufacturing of these composite parts beforehand.

The next step for validation of manufacturing simulation is to have the compression molding of the FBCC with chopped carbon fiber SMC material completed, and then pass the fiber orientation test results to enable a performance analysis with a well-developed virtual performance simulation (VPS) tool.

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