CONSIDERING PROCESS INDUCED PROPERTIES IN PERFORMANCE SIMULATION OF HYBRID COMPOSITE PARTS

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Abstract

Injection overmolding of hybrid thermoplastic composite parts combines thermoforming and injection molding manufacturing processes to make a single composite structure. This allows high rate production of cost effective parts that combine the structural performance and high complexity enabled by the individual processes. It is well known that aspects of the manufacturing processes influence performance of composite structures. Combining these processes to produce hybrid composite structures increases the complexity of these effects and necessitates accurate process-informed performance prediction.

Simulation of the manufacturing processes captures process induced fiber orientations. Process-informed, local material models are generated using micromechanical homogenization and then coupled with the performance simulation to better inform the performance prediction.

Initial design of hybrid composites requires assumptions about material properties and fiber orientations which do not account for the manufacturing process. Including as-manufactured material properties in the performance simulation provides insight to the performance of the as-manufactured structure. In this work, a comparison will be made between performance simulations which use as-designed material properties and performance simulations including process-informed, as-manufactured material properties.

Introduction

Hybrid composite parts enable rapid production of performance parts by combining different material forms and manufacturing processes used in conventional composite materials. Composite materials are seeing increased usage from automobile manufacturers to meet fuel efficiency and emissions targets [1] through reducing weight. Traditional thermoset composite manufacturing processes are severely limited by cost and production rate. Developments in thermoplastic composite manufacturing processes address these limitations but have constraints of their own. Injection molding of short fiber composites is growing in popularity for the low part cost and very high production rates. However, these materials typically lack the strength required in many structural applications. Thermoforming of continuous fiber reinforced thermoplastic materials, enables rapid production of structural components but part complexity is limited.

Injection overmolding of short fiber complex structures onto a continuous fiber reinforced thermoformed backbone, as shown in Figure 1, enables complex, structural, hybrid composite parts to be manufactured at the low cost and high rates demanded by the automotive industry [2], [3]. However, this manufacturing process has yet to be widely adopted. This slow adoption is primarily fueled by the limited knowledge and design tools available to accurately predict part performance. This is largely a result of a lack of knowledge and integrated design tools to accurately predict part performance [4]. The performance of hybrid composite parts is much more complex than their metal counterparts for a range of reasons. Conventional composite materials with a single material form already present design challenges from the fiber orientation and corresponding anisotropy of their properties. Using multiple material forms means designers must address the fiber orientations of all material forms utilized by the design.

The properties of composite materials are highly dependent on the orientation of the fiber reinforcements as any alignment of fibers results in anisotropy. Initial design of a part requires assumptions about the orientations of the fibers which lead to assumed, "as-designed" properties. In these high rate processes, the fibers contained by the material become oriented by the process leading to fiber orientations which result in "as-manufactured" material properties. These properties may differ significantly from initially used, as-designed properties.

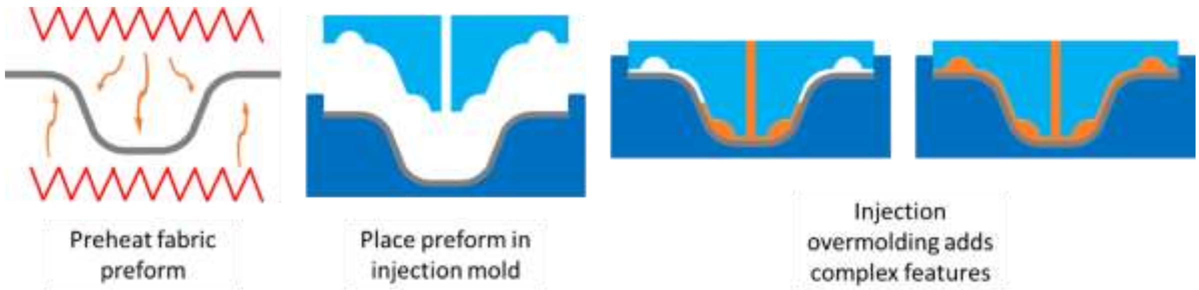

Figure 1: The hybrid injection overmolding process studied uses a woven fiber reinforced organo-sheet which is preformed and trimmed in a separate step before being preheated and placed in the injection mold. This improves control of the preform location and temperature during processing.

Commercial manufacturing process simulation tools exist to evaluate manufacturability and address the manufacturing effects of the injection molding and thermoforming processes for thermoplastic composite materials. These simulations use models of the material behavior during the manufacturing process to predict how processing will influence the fiber orientations. These orientations are very important due to local variations causing local variations in properties.

However, the interfaces between the tools, especially those which allow the properties of the continuous fiber preforms to be considered in the warpage part of the injection molding simulation, are limited. There has been recent work on utilizing manufacturing simulations for the individual steps to predict hybrid composite fiber orientations and resulting part performance [5]. Additional work by Yaldiz et. al. [6] attempts to fill the missing links between the commercial tools. The present work builds on these ideas to improve the flexibility of the simulation process, enable warpage simulation considering the anisotropic preform properties within the overmolding simulation tool. The significance of using the manufacturing informed material properties in performance simulations as compared to assumed design properties will also be evaluated.

Manufacturing Informed Performance Simulation Process

The complexity of the manufacturing processes used to produce these hybrid composite parts necessitates the use of specialized simulation tools to efficiently and accurately simulate the manufacturing processes. These tools provide insight to the producibility and processing conditions of composite parts manufactured through thermoforming and injection molding processes allowing engineers to inform design decisions before a prototype is produced. This reduces the time and cost of the design process.

However, these tools are often designed to be used independently and have not yet been completely integrated and evaluated for the production of hybrid composite structures which feature numerous manufacturing physics through multiple steps. Thus a simulation process was developed to facilitate the integration of the separate commercial tools [7]. Further developments have been made increasing the flexibility of the process, shown in Figure 2, to work with more commercial software packages through custom data transfer scripts.

The process begins with a CAD file of the initial part design which is used to design tool and ply geometries for the thermoforming simulation. The thermoforming simulation can then be performed in one of several commercially available tools. The fabric tow orientation results are then transferred to Moldex3D for the injection overmolding simulation. The overmolding simulation predicts the as-manufactured fiber orientations of the fibers contained in the overmolding material. Using the micromechanics based material models from Digimat, the fiber orientations inform the orientation dependent, local, material properties for both the fabric material and the discontinuous fiber reinforced overmolding polymer. These material properties are then coupled with a performance simulation in a commercial FEA package, such as ABAQUS or LS-DYNA, enabling more accurate prediction of as-manufactured part performance.

The process examined in this study limits its scope to the effects of including manufacturing process induced fiber orientations to the performance simulations. However, coupling additional results of the process simulations such as thermal history and residual stress are of interest for future work.

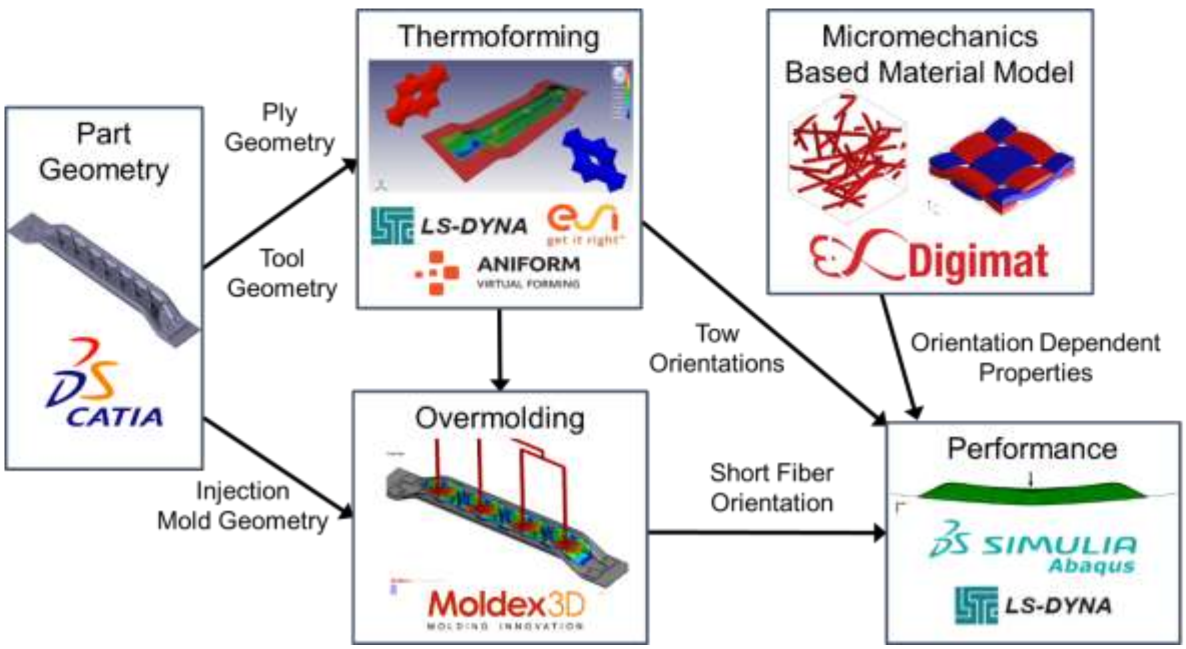

Figure 2: The manufacturing informed performance simulation workflow develops the links to transfer data between the different design, manufacturing, and performance simulation software tools.

Generic Complex Beam

To demonstrate the effect of including as-manufactured material properties, a generic complex beam structure with features representative of those used in potential applications of hybrid composites was adapted from previously produced hybrid composite beams used to empirically study the hybrid molding manufacturing process [8]. The beam features a thermoformed, woven, glass reinforced polyamide organo-sheet which serves as the structural backbone of the part. In this case, the organo-sheet is thermoformed in a separate tool allowing for greater control of the process. The sheet is then trimmed to shape before being placed in the injection molding machine. The beam is overmolded with “long” glass fiber reinforced polyamide to create rib structures which increase the torsional stiffness of the structure. The original beam design also features metal bushings and cavities for the insertion of unidirectional tow reinforcements shown in Figure 3. These features are not yet included in the current work as experimental test results of the beam are not considered.

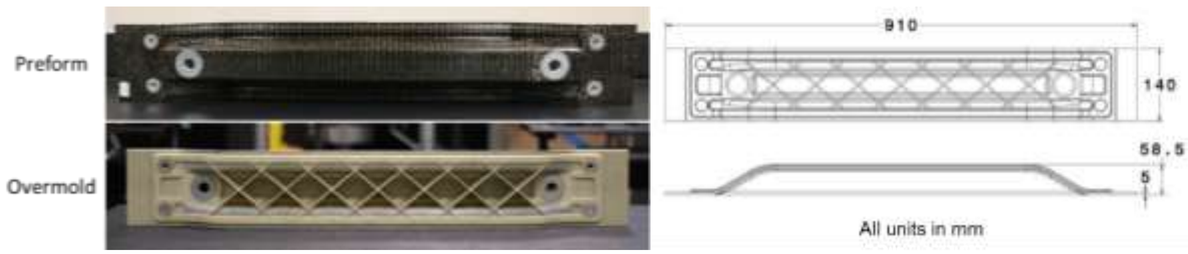

Figure 3: The example complex generic beam contains features, such as webs, necessary for automotive structural applications

Manufacturing Process Simulations

Thermoforming Simulation

The shape of the continuous fiber reinforced preform is extracted from the part geometry and is offset and extended to design tools for the thermoforming process. In this case, an approximate initial ply shape was also developed starting from the CATIA composites ply flattening tools. Meshes representing the organo-sheet and the tool surfaces were assembled and run using an explicit analysis in LS-DYNA as shown in Figure 4. The organo-sheet was modeled using the MAT249 material model designed for composite part forming.

Simulating the thermoforming process through an explicit finite element model provides information about the manufacturability of the part. This can help predict if the fabric is likely to develop wrinkles or tear during manufacturing. Corrections to the process and part design can then be made before expensive tooling is manufactured.

Composite materials exhibit properties which are highly dependent on their microstructure and woven organo-sheet materials are no exception. The local microstructures of these materials are influenced by the manufacturing process leading to tow orientations which may differ from their original state beyond only conforming to the out of plane contours of the part due to low shear stiffness of the material during processing. The simulation of the thermoforming manufacturing process provides the as-manufactured microstructure in the form of vectors containing local tow orientations. These orientations will be used to inform as-manufactured effective properties.

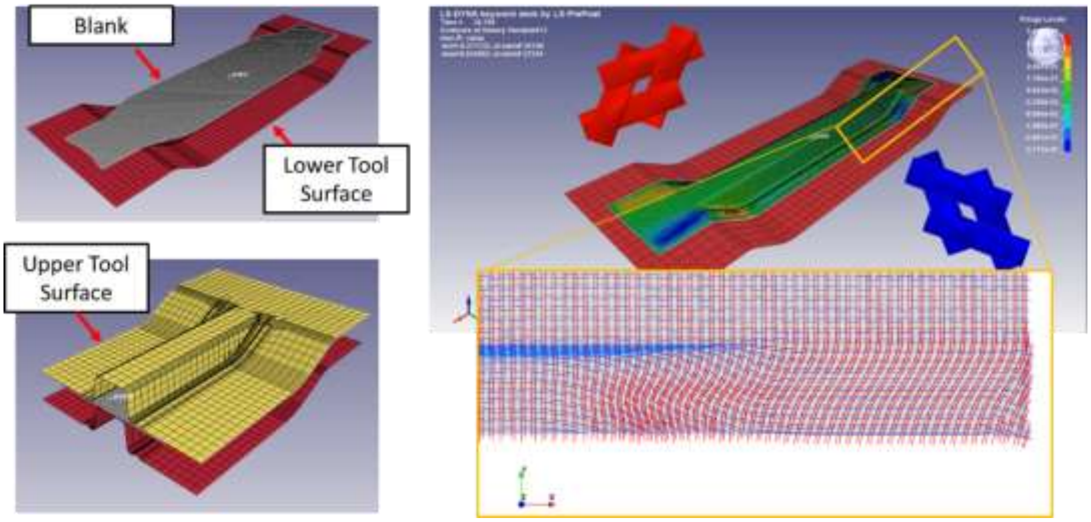

Figure 4: Thermoforming simulation in LS-dyna provides as-manufactured fabric tow orientations.

Injection Molding Simulation

An injection molding tool design is developed from the part geometry including runners and cooling channels which will enable rapid production of the part. Simulation of the design, using Moldex3D, enables rapid iteration of runner and cooling channel designs to test their effectiveness early in the design process. This ensures that adequate fill time and sufficiently uniform cooling will be achieved. Shown in Figure 5 is the example tool design used in this work with cooling channels extending between the ribs to ensure the center of the part cools quickly. A hot runner manifold was used to efficiently fill the relatively large part.

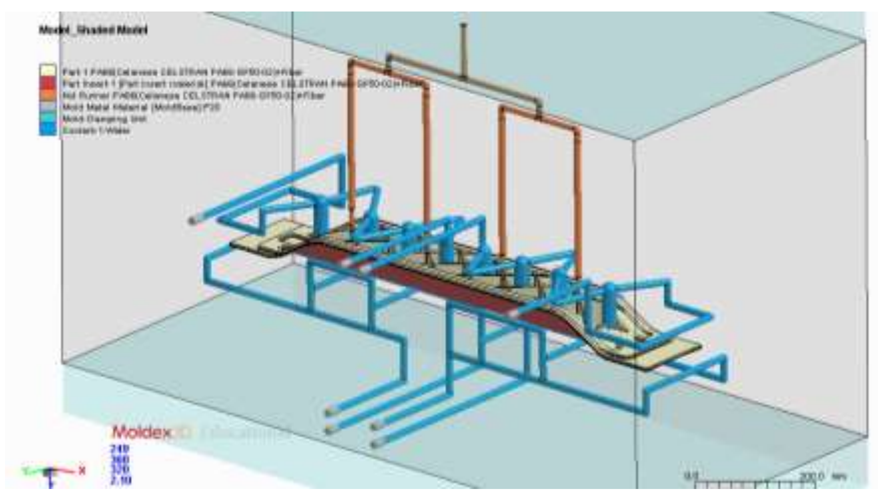

Figure 5: Injection molding simulation of generic complex beam in Moldex3D simulates the effects of chosen runner system, gate locations, and cooling system.

Material properties for the overmolded glass fiber filled thermoplastic were taken from a PA66 in the Moldex3D database which contained 40wt% long glass fibers. Additionally, the woven preform is included in the simulation to account for the heat transfer to the preform as well as the mechanical properties used in the warpage simulation. However, the mechanical properties of the preform must include the as-manufactured tow orientations to produce an accurate result.

This requires the use of a custom data mapping script to transfer the results of the thermoforming simulation shell mesh to the injection molding solid element mesh.

With simulation of the overmolding process, problems such as trapped air or weld lines can be identified. The tool design can then be quickly modified to eliminate these issues before expensive tools are made. Regions which require additional cooling can also be determined and various cooling channel designs may be tested quickly and efficiently.

The discontinuous fibers contained within the overmolded thermoplastic reinforce the material but their effect on the properties is highly dependent on their orientation. These discontinuous fibers are oriented by the flow through the mold which can be modeled using Jeffery based equations. The improved anisotropic rotary diffusion model is used to predict how the long glass fibers become oriented in this part during the filling process which are expressed as an orientation tensor [9]. These flow-induced fiber orientations can then be used with a microstructural model to predict the effective performance properties of the material. The axial components of the fiber orientation and resulting effective modulus are shown in Figure 6.

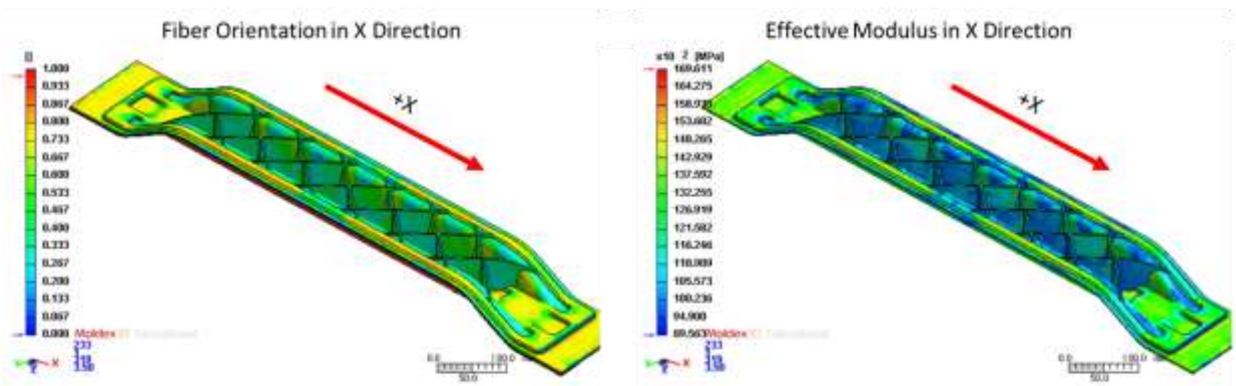

Figure 6: Overmolding process simulation results for flow induced axial fiber orientation and resulting as-manufactured effective axial modulus prediction

The overmolding simulation can be used to predict part warpage which considers the thermal history as well as the flow induced fiber orientations. Moldex3D is capable of including anisotropic thermomechanical properties of the fabric insert which will improve the accuracy of the warpage simulation results. A tool provided by Moldex3D allows tow orientations from some LS-DYNA thermoforming simulations to be included in the warpage simulation. In order to improve the flexibility of the simulation workflow, a customized mapping script was developed to map as-manufactured tow orientation process simulation results to the Moldex3D model. The new script enables the use of major thermoforming simulation tools which output results in the form of tow orientation vectors including LS-DYNA, PAM-FORM, and AniForm.

Incorporating Manufacturing Process Simulation Results to Performance Simulation

After obtaining the manufacturing simulation predictions of the composite fiber orientations for both the organo-sheet thermoforming and injection overmolding processes, the properties are then used to predict effective mechanical properties of the structure. These as-manufactured effective properties will allow more accurate prediction of the as-manufactured part performance under load as compared to the idealized effective properties used in the initial design.

Performance simulations for composite structures require sufficient reduction in detail to be run efficiently but adequate fidelity to capture the local behavior due to changes in microstructure. A micromechanical homogenization tool such as Digimat can be used to combine the orientation results from the manufacturing simulation with known properties of the fiber and matrix materials to predict orientation dependent, local, effective material properties (Figure 7). This tool utilizes Mori-Tanaka mean field homogenization to couple the manufacturing simulation results to the performance simulation behavior.

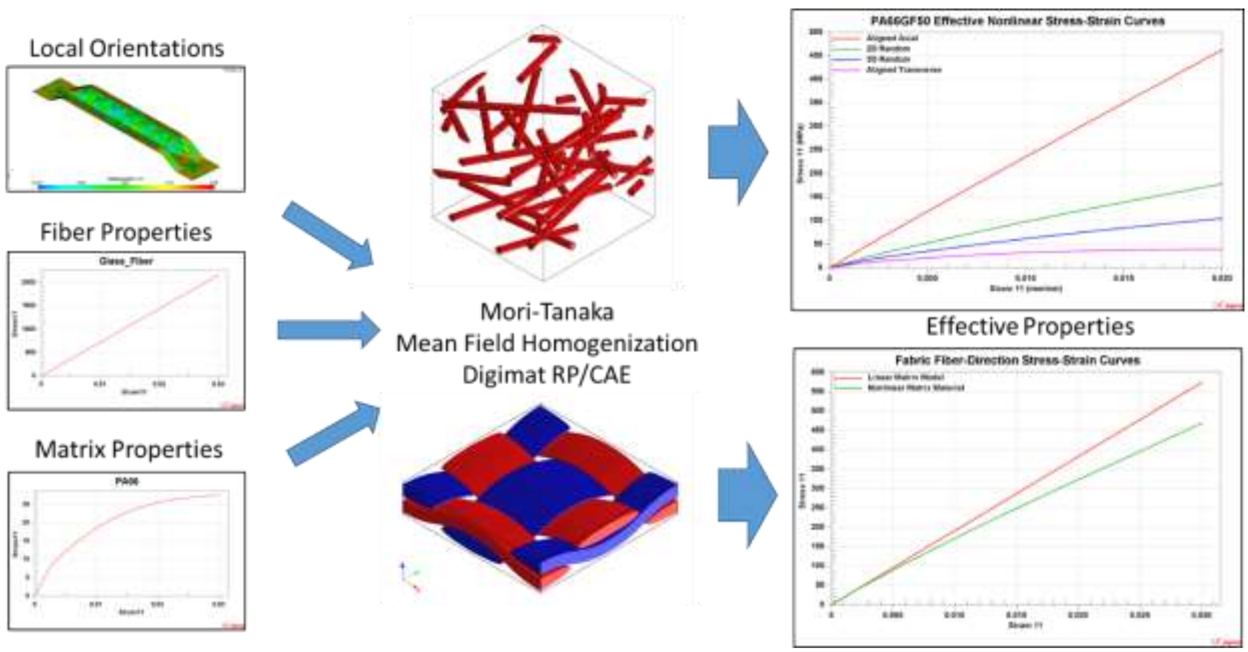

Figure 7: As-manufactured fiber orientations from manufacturing simulations informs overmolding material effective properties to be used in ABAQUS performance simulation through micromechanics model in Digimat

The effect of including these local orientation dependent properties in a performance model was examined using a three-point bend test applied to the generic, complex, hybrid composite beam as shown in Figure 8. A fixed displacement was applied in a quasi-static simulation in ABAQUS and the force required was measured. This provided insight to the effective stiffness of the beam structure.

Four cases were compared as shown in Table I. The as-designed material models are based on homogeneous, idealized fiber orientations which do not account for manufacturing induced fiber orientations. The tow orientations in the woven preform are assumed to be perpendicular but still conformal to the surface of the beam. Discontinuous fibers are idealized as randomly oriented in three dimensions for the overmolded material. The properties are calculated using the same mean field homogenization model for these idealized orientations and are applied to the entire set of elements representing that material regime.

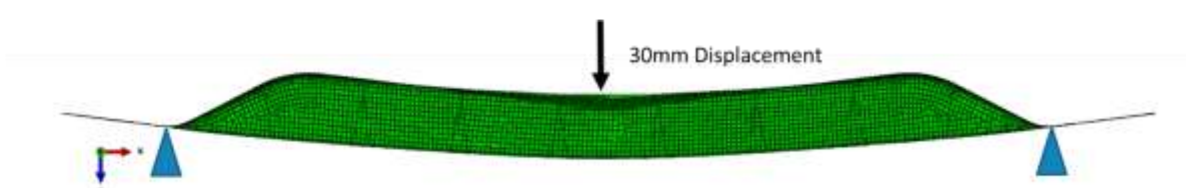

Figure 8: Three-point bend quasi-static stiffness performance is tested in an ABAQUS finite element analysis using shell elements with properties coupled to as-manufactured fiber orientations with Digimat.

Table I: Performance simulation reaction force comparison between assumed (as-designed) and process simulation informed (as-manufactured) fiber orientations

Run	Preform Material Model	Overmold Material Model	Reaction Force (N)	% Change from As-Designed
1	As-Designed	As-Designed	12700	0
2	As-Manufactured	As-Designed	13100	3.1
3	As-Designed	As-Manufactured	13200	3.7
4	As-Manufactured	As-Manufactured	13800	8.4

As-manufactured material models include the manufacturing simulation fiber orientation results. These are applied to each material regime individually to determine their effects. Finally, a full as-manufactured performance simulation is considered which includes manufacturing induced orientation effects to the entire hybrid composite structure. The as-manufactured performance simulation predicts an effective stiffness which is 8.4% greater than that predicted by the idealized as-designed prediction.

In addition to a change in effective stiffness, the load paths change significantly due to the local fiber orientations. Figure 9 shows that the stresses in the overmolding material change shape due to the change in axial fiber orientation. Examining the axial stress in Figure 10 shows that a higher tensile stress occurs in the preform of the as-manufactured performance simulation as compared to the as-designed simulation. This is expected considering the increase in beam deflection force and thus effective stiffness. However looking back at Figure 9, the magnitude of the maximum compressive stress in the overmolded material is very similar to that of the as-designed case at the center of the beam. This indicates that the preform carries a higher proportion of the load in this region which is likely due to the low axial fiber orientation at the melt front convergence location at the center of the beam.

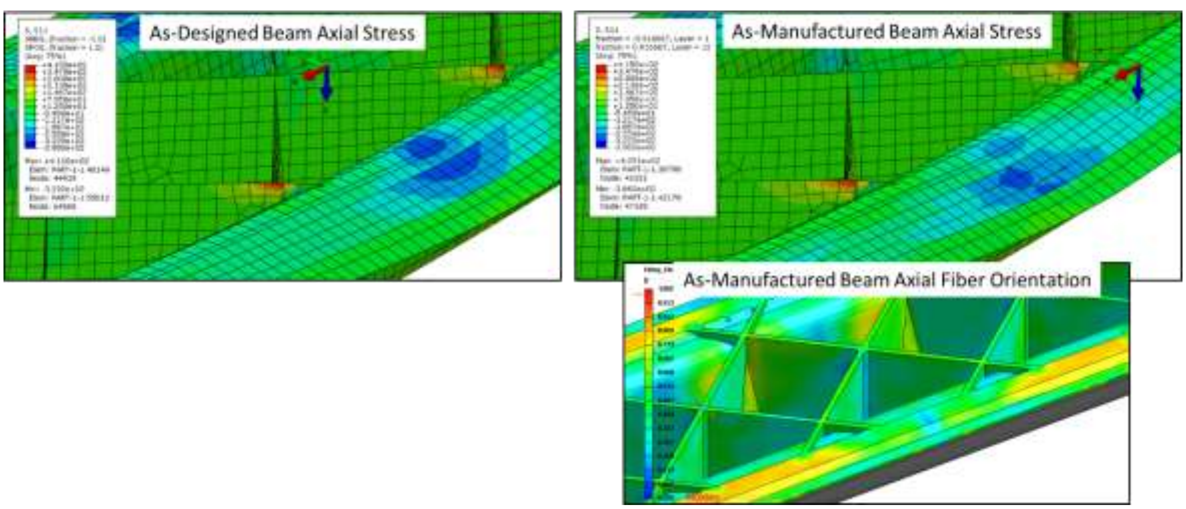

Figure 9: The performance simulation stress distribution in overmolding material for Run 1 (left) and Run 4 (right) shows the difference in stress distribution due to fiber orientation dependent material properties.

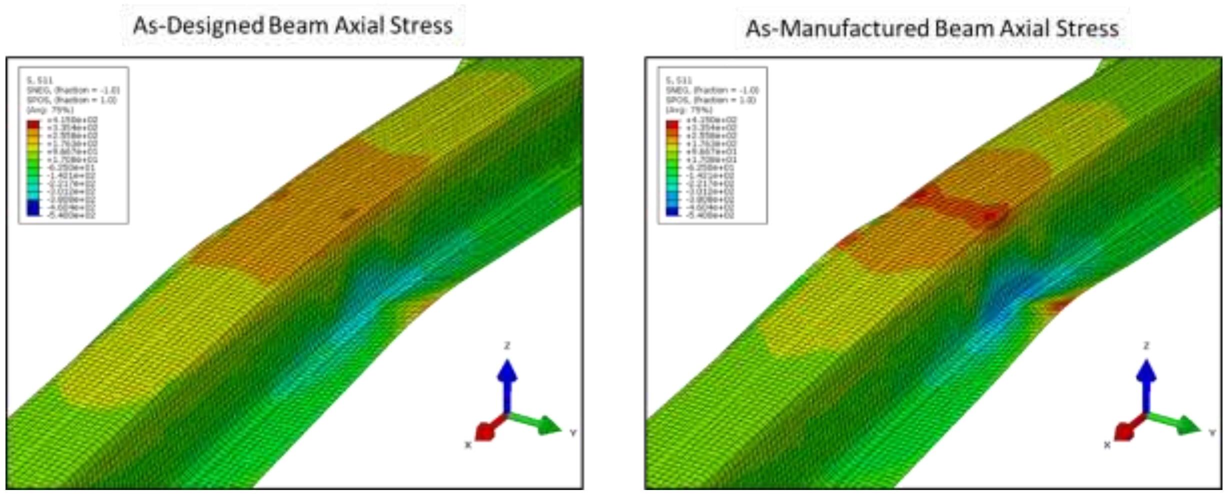

Figure 10: The performance simulation stress distribution in overmolding material for Run 1 (left) and Run 4 (right) shows increased axial stress in the preform when considering as-manufactured fiber orientations caused by a change in load path.

Conclusions and Next Steps

The performance simulation results presented show a difference in effective stiffness and change in load path for a hybrid injection overmolded composite structure when comparing simulations using as-designed versus as-manufactured material properties. This shows that the performance of these hybrid composite structures is highly dependent on the manufacturing process and that simulating the manufacturing process can allow processing effects on fiber orientations to be considered in the design process. Iterating this process can be used to optimize the design such that the as-manufactured part will meet all design requirements without being overdesigned and thus overweight.

In addition to stiffness, further improved models will need to include failure predictions in dynamic loading to anticipate performance in critical structural applications, especially for the automobile and aerospace industries. Due to the dissimilarities of the materials, there are likely to be high residual stresses in the part which could have a significant effect on the onset of failure. Experimental material characterization and model validation is still necessary to demonstrate the accuracy of the results of the simulation workflow. The manufacturing simulations also have capabilities to capture other process dependent effects such as the thermal history. Modelling of the thermal history dependent bond between the materials would further improve the capabilities of manufacturing informed performance.

Acknowledgements

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