A Validation Study of a Physics-Based Tack Model for an Automated Fiber Placement Process Simulation

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1 ABSTRACT

Automated Fiber Placement (AFP) offers a fast and more repeatable alternative for the fabrication of complex composite parts compared to traditional methods such as hand lay-up. Despite the performance advantages in the AFP process, geometry and process conditions may introduce defects that are not common in a hand lay-up process (e.g. wrinkles, puckers, fiber bridging, etc.). All of these critical defects are a form of fiber misalignment due to separation of the prepreg slit tape from the substrate.

This research project, performed under NASA's Advanced Composites Project, offers a physics-based framework for simulation of AFP processes with the aim of predicting defects as a function of tool geometry, tow course path, and process conditions including temperature, head speed, pressure, and tow tension. The physics-based framework includes a representation of the AFP head, the slit tape, and the substrate. A key component of the model is the tack that is formed between the substrate and the slit tape during deposition. A rate-dependent cohesive model is developed to simulate the complex tack response between the two surfaces. Previous papers and presentations by the authors focused on the tack model development and validation; however, this paper focuses on the simulation framework and sensitivity due to the simulation setup (e.g. element type, section definition, mass scaling, damping) and its affect on defect prediction.

2 BACKGROUND/INTRODUCTION

Although tape placement methods are more efficient in the manufacturing of composite parts, these processes introduce defects that are not common in less efficient hand-layup processes. These AFP defects involve excess length in the form of puckers, wrinkles, tow splitting, or folds in the prepreg tape as a result of steering and residual stresses induced during placement, shown in Figure 1. The adhesion between the prepreg tape and substrate, known as "tack," is the key resisting phenomenon to defect formation. Accurate representation and modeling of tack is fundamental to a process model for AFP defect prediction [1-3]. The quality of tack is highly dependent on the temperature and pressure history determined by the process conditions (e.g. tow tension, compaction force, temperature, speed, etc.) and geometry. Previous articles by the authors [4-6] presented a physics-based framework developed by Convergent-US to simulate tack. The finite element simulation of AFP process includes

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many components that interact in a complex manner. This paper focuses on setting up the AFP simulation framework and various aspects of it.

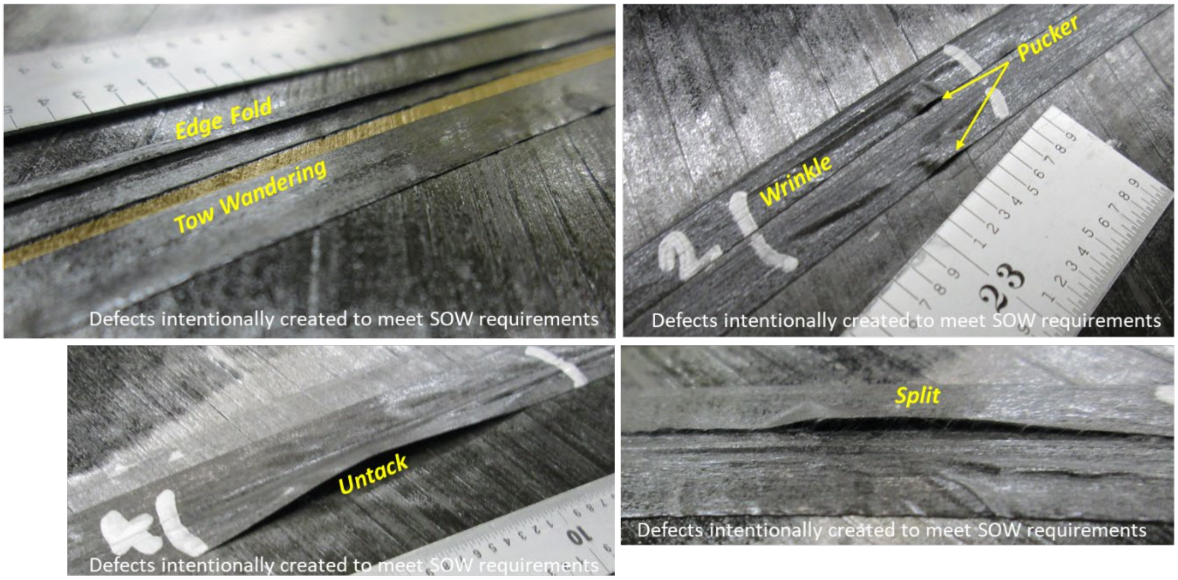


Figure 1. Typical AFP defect types.

3 MODEL SETUP

The physics-based finite element simulation of the AFP process developed under this project includes representation of the key components and physical phenomena involved. Abaqus/Explicit is chosen as the finite element solver.

These key components include representation of the tows being placed, the AFP head (roller, tow guide), and the substrate. Interactions between tows and the substrate (tack), the roller and tows, and the roller and substrate are also captured in the finite element simulation. In this simulation framework, the deposition path (course path) is captured through enforcing displacement boundary conditions to the substrate. Figure 2 summarizes the applied loads and boundary conditions in the simulation. AFP simulations have also been developed for multi-tow heads on complex curvature tools, as shown in Figure 3.

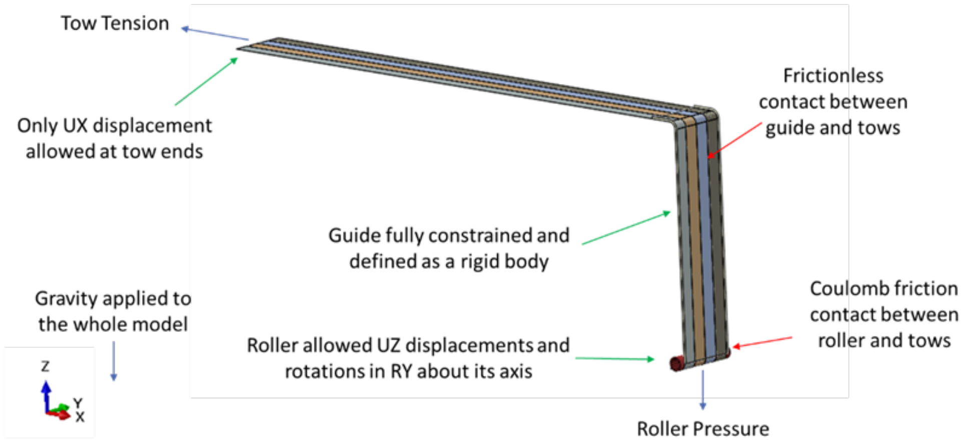


Figure 2. Description of loads, boundary conditions, and contact interactions in the AFP simulations.

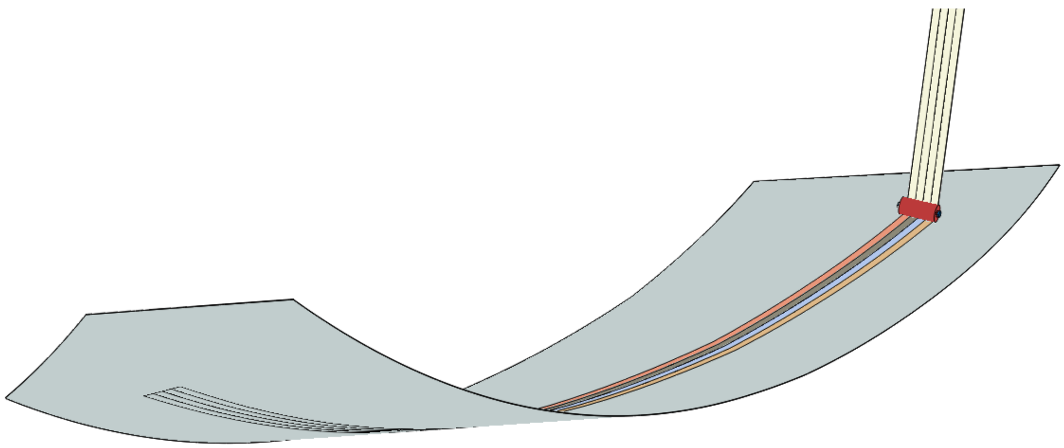


Figure 3. Multi-tow AFP steering simulation for complex curvature course path.

To validate the capability of the simulation framework to predict AFP defects, a building-block approach is adopted. This includes steering with a constant radius on a flat surface, deposition of a single-curvature tool and finally deposition on a complex curvature tool.

Figure 4 shows the model for deposition of a single tow on a flat arc. As shown, the model is comprised of the tow, the tow guide, the AFP roller and the substrate. In this simulation, the head is held stationary and the substrate rotates to simulate the deposition kinematics.

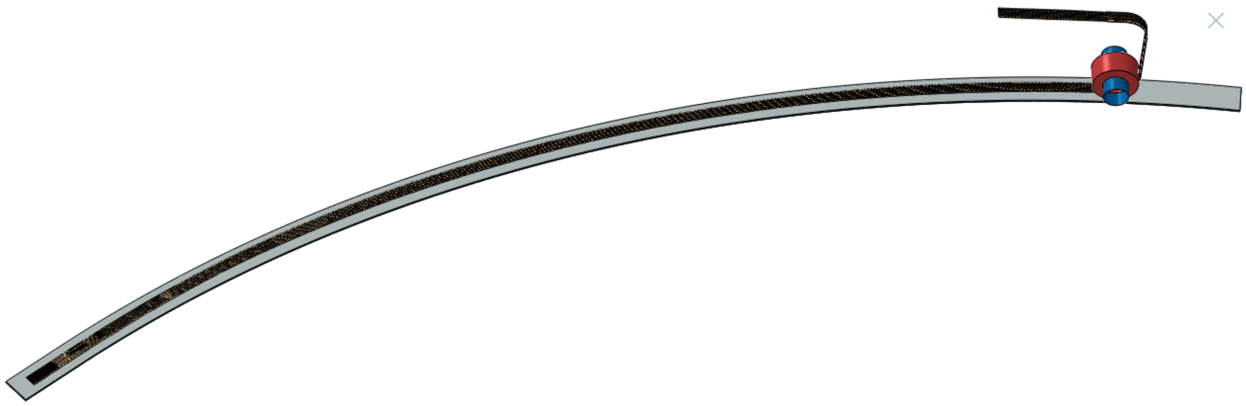


Figure 4. AFP steering simulation of a flat arc.

4 VALIDATION APPROACH

Validation of this complex process model must be carried out in the constitutive model as well as the implementation in a 3D finite element model in Abaqus/Explicit. This paper focuses on the complexity and sensitivity of a simplified 3D AFP steering simulation (flat tool, constant radius, single tow on a defect free prepreg substrate) due to simulation setup including element type, mass scaling, bulk viscosity, and application of loads/boundary conditions as well as material property sensitivity for properties where no experimental data exists or for properties that are difficult to measure.

4.1 Tack Model Validation

A physics-based rate-dependent cohesion and decohesion tack model was developed and calibrated to experimental test data. The details of the tack model physics and development are discussed in previous papers [4-6].

The capability of the tack model to predict the temperature and rate-dependencies observed in the experiments was validated against the University of Nottingham peel test, outlined in [7,8]. In those experiment, the tack between prepreg surfaces was measured by the peel force required to separate the surfaces. Time-temperature superposition using the Williams-Landel-Ferry (WLF) function was employed to collapse data sets that were obtained at different temperatures and develop a master curve. Similar shifting was employed to visualize the tack model predictions. Figure 5 shows the tack model prediction against the University of Nottingham peel test data [7] of an experimental resin. The tack model shows relatively good agreement with the test data and captures the trends in terms of temperature and rate dependencies for this particular case; however, more data points are needed in order to fully assess the quality of the fit given material variability.

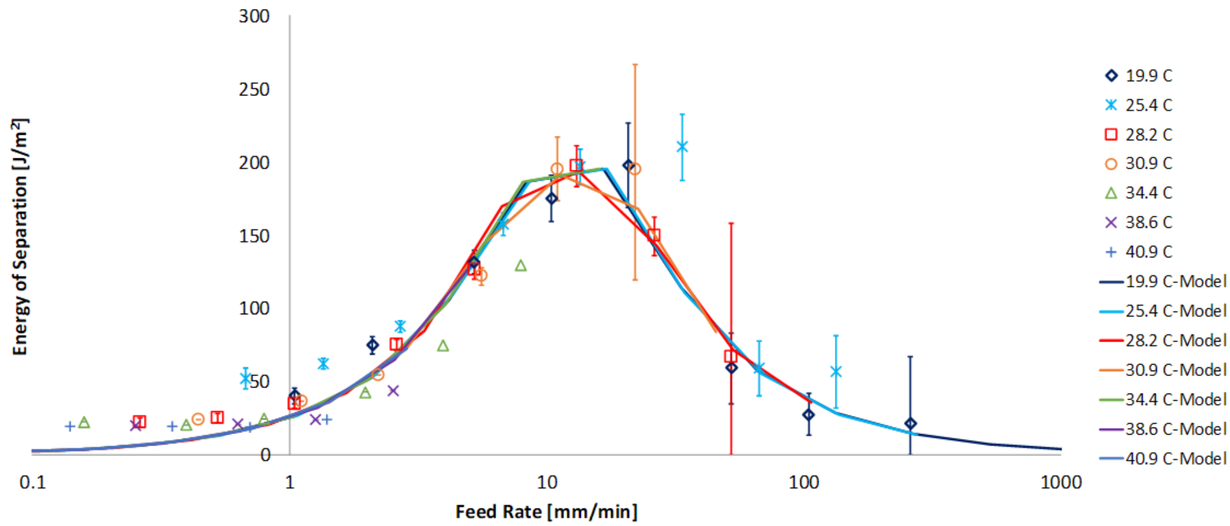


Figure 5. Energy of separation at shifted feed rates from peel experiments [7] compared with the tack model predictions.

4.2 Simulation Validation

The AFP steering simulation, containing the tack model constitutive relationships, process parameters, and geometry, must also be validated as a function of the implementation (i.e. simulation setup). A validation approach was used to determine the sensitivity of the AFP simulation to the Abaqus/Explicit parameters and to evaluate the effect of mass scaling, bulk viscosity, and section and element type. Additionally, prepreg properties (which are difficult to measure) must also be included in the sensitivity analysis to assess the influence on defect prediction. To assess the quality of the prediction, the total energy as well as the artificial strain energy and kinetic energy was evaluated.

4.2.1 Sensitivity Study

Within this sensitivity study, the simulation is evaluated for material property sensitivity as well as simulation setup in the case of a simplified flat constant radius single tow geometry. As part of the material property sensitivity, the prepreg in-plane shear stiffness contributes to the way excess length is accommodated during steering and therefore must be investigated. In reality, the in-plane shear deformation typically manifests in the form of tow splitting in the middle of a tow. In the finite element continuum model, the shear response is represented by the in-plane shear modulus (G_{12}).

Both the axial and bending stiffness will affect the defect prediction. In order to capture critical out of plane misalignment defects, the temperature-dependent bending response must be accurately represented in the model. At low temperature, the bending stiffness is high; therefore, there is more resistance to out-of-plane movement, resulting in defects with lower aspect ratios. Similarly, at high temperatures the bending stiffness is low, resulting in less resistance to out-of-plane movement, producing defects with higher aspect ratios.

In a simple curved arc, excess fiber length will occur on the inner edge, imposing a normal strain. The strain will produce a compressive load on the outer edge of the tow causing the material to buckle under a critical compressive strain. For an uncured tow, the axial and bending stiffnesses cannot be unified by standard continuum mechanics theories and should therefore be decoupled. In general, the bending stiffness is much smaller than what the axial stiffness would suggest which lowers the critical load necessary for fiber buckling. In the current simulation setup, the axial and bending stiffnesses are decoupled by superimposing membrane and general shell sections in the tow.

The simulation setup (i.e. parameters that do not directly correspond to the physical environment) including element type, mass scaling, and application of loads and boundary conditions are also included in the simulation validation. Multiple element types exist for shell and membrane sections. Reduced integration elements are prone to hour-glassing but are computationally more efficient compared to full integration elements that prevent hour-glassing behavior. Thin shell elements can also be used but assume negligible transverse shear flexibility if the thickness is less than 1/15 of the shell surface length. Small-strain shell elements assume small membrane strains and are computationally efficient but must be closely monitored for artificial strain. The mass scaling is also an important parameter for simulation optimization in terms of computational time. However, too much mass scaling can result in artificial energies in the simulation which will convolute the prediction.

5 RESULTS

Given the ongoing nature of this work, only the sensitivity due to in-plane properties and bending stiffness are shown below. In an AFP steering simulation for a simple curved arc of 0.889 m (35 inches) depositing at 0.14 m/s, the in-plane transverse and shear properties were evaluated for their effect on defect formation/prevention. Figure 6 shows the higher in-plane stiffness prevents in-plane deformation allowing for excess fiber length to be dissipated as out-of-plane deformation. Additionally, there is a reduction in the size of defects when shear deformation is promoted through the lower in-plane stiffness.

The influence of bending stiffness in the fiber direction (D_{11}) within the stiffness matrix, specified in the general shell section, is shown in Figure 7. Here, the higher bending stiffness correlates to fewer but larger defects. This effect may be due to more fiber length under compression prior to buckling, resulting in increased excess length after buckling.

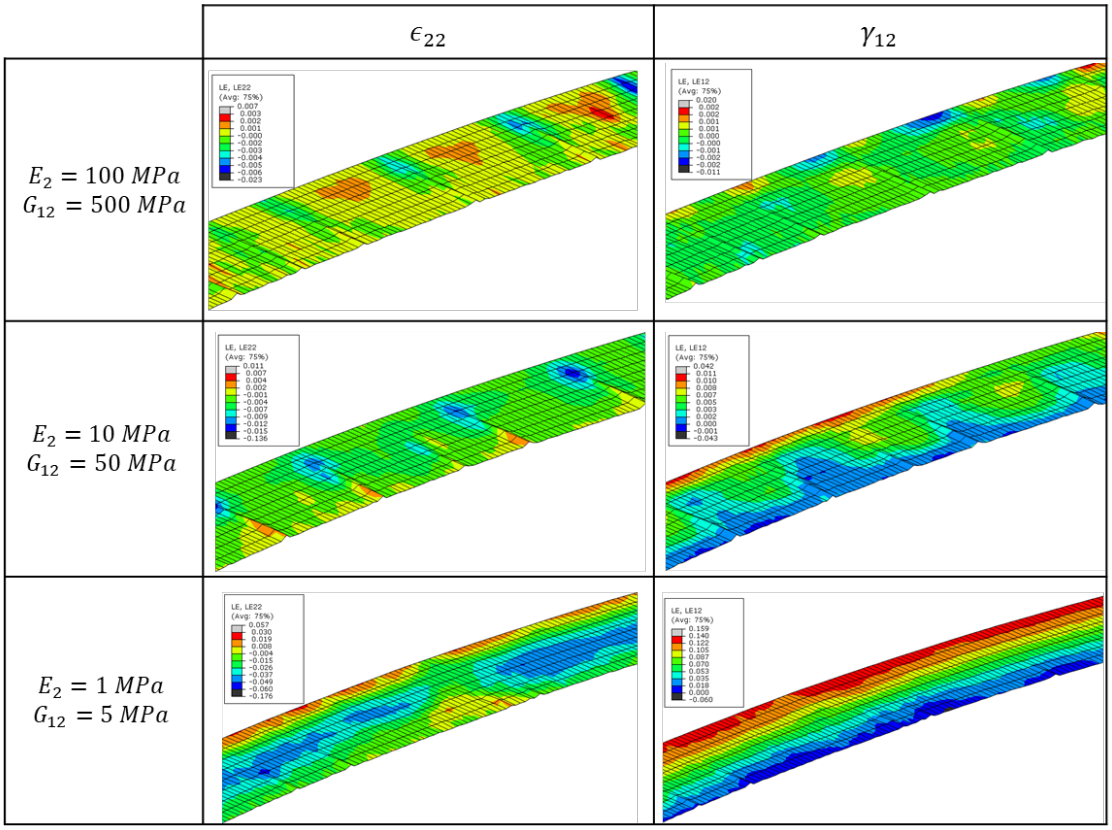


Figure 6. Simulation results for varying in-plane properties in deposited tows for a simple 0.889 m arc deposited at 0.14 m/s.

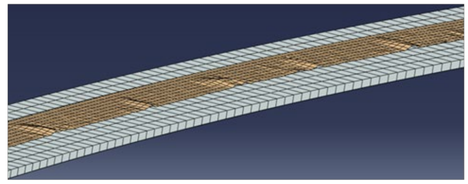
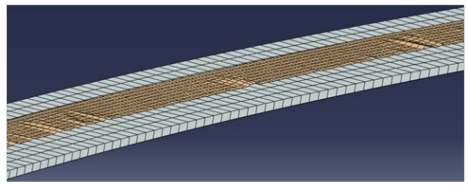
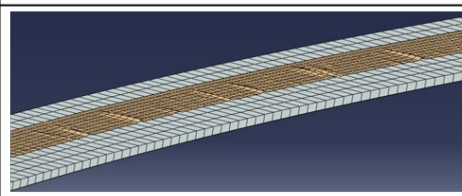
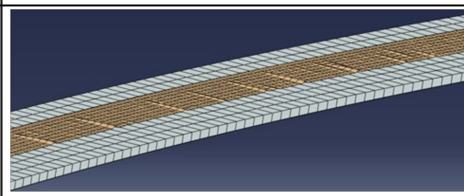
$D_{11} = 2 \times 10^{-3}\ N$	
$D_{11} = 10^{-3}\ N$	
$D_{11} = 10^{-4}\ N$	
$D_{11} = 10^{-5}\ N$	

Figure 7. Simulation results for varying bending stiffness in deposited tows for a simple 0.889 m arc deposited at 0.14 m/s.

6 CONCLUSIONS

A complex physics-based simulation including a rate dependent tack model has been developed. Currently, the simulation setup is being evaluated to assess the sensitivity due to simulation setup including element type, mass scaling, bulk viscosity, and application of loads/boundary conditions as well as material property sensitivity for properties where no experimental data exists or for properties that are difficult to measure. This evaluation will result in the verified implementation of the AFP steering environment for a simple curve, allowing for scale-up and validation with experimental data.

7 REFERENCES

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