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TOW-DROP AREAS INFLUENCE ON COMPOSITE LAMINATES IN AUTOMATED FIBER PLACEMENT

Félix THÉBAULT[1,2], Alexandre CLÉMENT[1], Sylvain FRÉOUR[1], Gwénolé LE MOAL[2] and Pascal CASARI[1]

[1]Nantes Université, Ecole Centrale Nantes, CNRS, GeM, UMR 6183, F-44600 Saint-Nazaire, France
Email: alexandre.clement@univ-nantes.fr, Web Page: https://www.univ-nantes.fr/alexandre-clement

[2]CIMPA S.A.S., 1 avenue André-Marie Ampère, 31770 Colomiers, France
Email: felix.thebault@cimpa.com, Web Page: https://www.univ-nantes.fr/felix-thebault

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Abstract
Composite materials are used in industry due to their superior strength-to-weight ratio compared to metallic materials. One prevalent manufacturing process for composite parts is Automated Fiber Placement (AFP). However, this process is subject to inherent limitations that can result in the formation of resin pockets or overlaps. These can appear at tow-drop areas, which are a typical type of design singularity. The lack of knowledge about these singularities leads to the use of conservative knockdown factors to ensure the mechanical compliance of parts. This paper introduces a preliminary numerical model depicting standard tow-drop areas on a laminated plate. The impact of varying incidence angles of adjacent courses on the mechanical state of the plate is explored through simulation work. Initial results indicate that resin-rich zones significantly affect the internal mechanical state of the plate, leading to local stress concentrations and increased deformation. As the angle of incidence increases, these impacts become more pronounced, along with the effects of fiber disorientation.

1. Introduction

1.1. Context and problem presentation

Composite materials, and cross-ply laminates in particular, play a pivotal role in industry due to their capacity to withstand high loads while being lighter than traditional materials. One of their limitations is the difficulty to automate the process of manufacturing. An arising process called Automated Fiber Placement (AFP) offers advantages such as increased speed, reproducibility, and precision of parts manufacturing. In this process, multiple tows of carbon are deposited on a tool surface, creating plies. This is achieved by mounting a laying head on a robot arm or gantry structure. To ensure proper adhesion, the carbon tows are heated and compressed during deposition. The resulting collection of plies with different orientations creates a preform, which is typically pressure-cooked in an autoclave before being cut and assembled into the final part [1,2].

Automated Fiber Placement (AFP) technology is frequently selected over other automated draping techniques due to its capacity to achieve high-quality deposits on complex surfaces, enabling the deposition of composite courses with greater curvature. Nevertheless, errors may occur during various stages of manufacturing, creating heterogeneities in the part. This leads AFP part designers to adopt a conservative approach, incorporating safety factors to ensure that manufactured parts meet the specified dimensional criteria [3], and necessitating the constant inspection of deposited plies. Thus, the lack of comprehension regarding the influence of those heterogeneities on manufactured parts constrains the potential of the AFP process, which has yet to be fully realized.

Among the phenomena jeopardizing AFP potential, interest is growing around the effects of tow-drop areas [4]. There are two terms used to describe heterogeneities in a composite part: defects, which refer to unforeseeable errors occurring during manufacturing, and singularities, such as tow-drops, which are predictable artifacts resulting from process limitations. Tow-drops consists of individual tows being dropped, and is intrinsically linked to the AFP process. Indeed, as the deposition head places multiple tows in parallel during a single pass to enhance productivity, these parallel tapes form a course deposited by the laying head. Trajectories of the head are generated using a guiding curve, which is subsequently shifted using one or more possible methods (shifting method, parallel method or manual definition) to generate deposition trajectories across the entire surface of the part [5]. It is possible for consecutive courses to diverge or converge on double-curved parts, creating singularities such as those shown in Figure 1, provoking tow-drops. These must be addressed either by inserting tows to fill the gaps created by diverging courses or by dropping tows from colliding courses to align with previous ones [4].

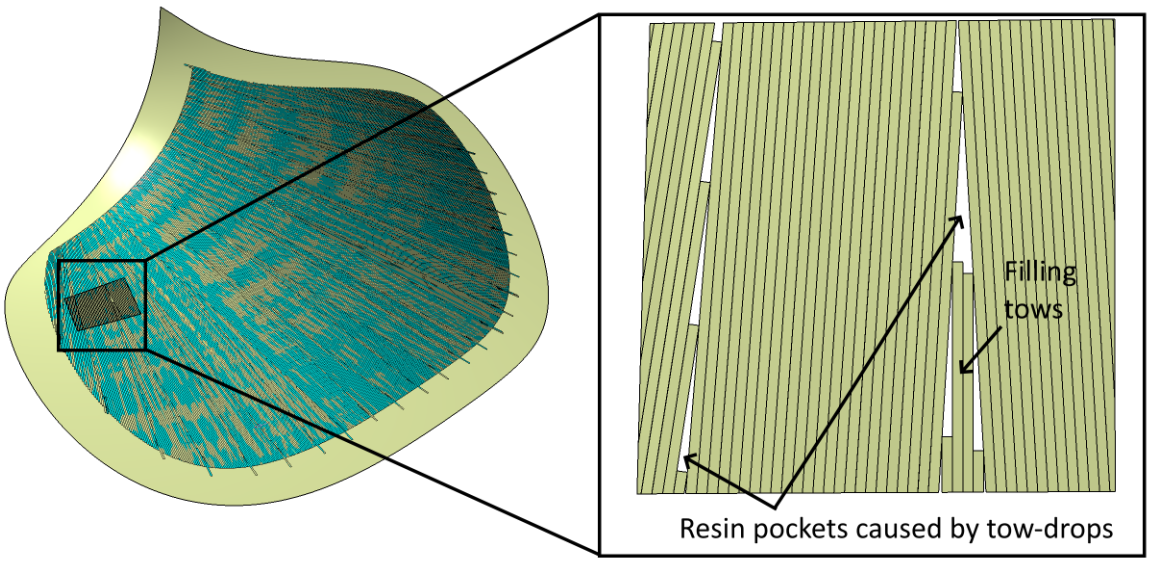


Figure 1. Representation of a tow-drop area on a ply.

The greater the number of parallel tows within a course, the less significant the applied curvature radius can be, as it increases compression stresses on the tows within the turn [5]. Additionally, design offices require that the angular deviation of a course be limited to a bounded interval to ensure parts can withstand desired loads. These two constraints often limit the manufacturing of double-curved parts and lead to tow-drops during course deposition.

To address these tow-drops, three solutions can be considered: full overlap, full gap, or partial gap/partial overlap [4]. Considering a full overlap, a local thickness increase occurs, which can result in irregular surface quality and a reduction in buckling resistance due to waviness in the fiber plane. Conversely, not overlapping the gaps creates resin-rich pockets that may not be fully eliminated by pressure applied by subsequent roller passes or by fiber sliding due to pressure in the autoclave and resin flow movements. Usually, industrial parts must have a surface that is as smooth as possible in order to meet assembly tolerances, thus the full gap approach is often the preferred option. This approach will therefore be further investigated in this study, and the influence of resin rich pockets on the mechanical states of composite laminates in particular.

Resin rich pockets generated by the full gap method will result in a singularity within the ply, whose geometry and location are predictable. This type of singularity can be approximated in a plane as a triangular shape, with dimensions influenced by the width of the tows and the angle of incidence between

the two courses. Consequently, the greater the width of the tow, the larger the area of the defect. By varying the angle of incidence, denoted by Δα, the resin pocket can be either thin and elongated or wider and shorter, as illustrated in Figure 2.

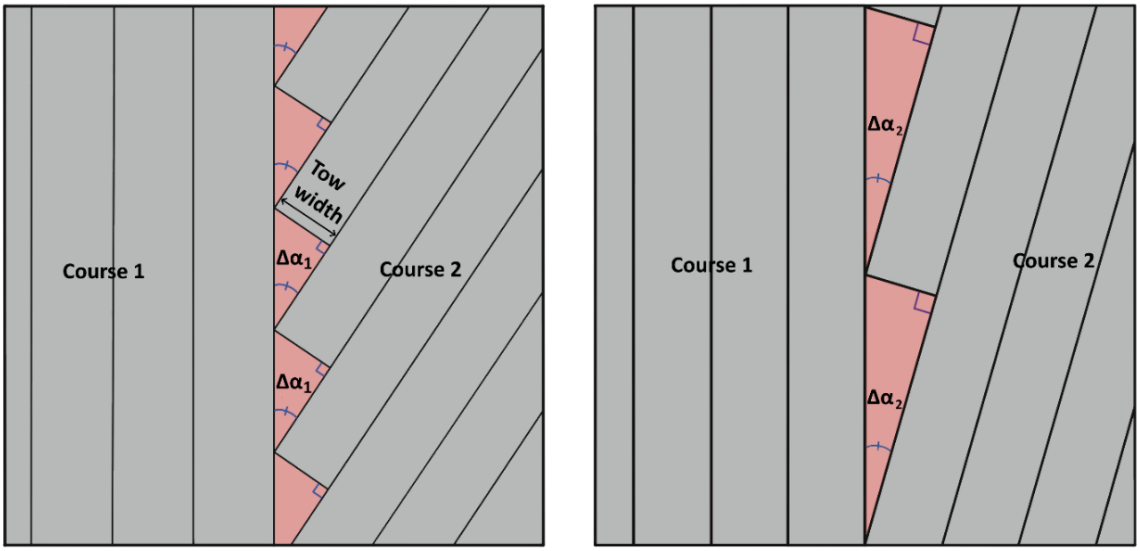


Figure 2. Planar representation of the resin pockets caused by tow-drops.

1.2. Literature review

The study of defects and singularities generated by the AFP process is quite a well-established field of research. Heinecke and Willberg in 2019 [3], proposed classifications of defects along with their conditions of occurrence and potential effects on the produced parts. These works provide an overview of experimental and numerical simulation studies aimed at better understanding the effects of defects on parts manufactured by AFP. Among these experimental works, the significant test campaign conducted by Croft et al. in 2011 [6] on specimens with embedded defects should be mentioned. Their study focused on the influence of isolated defects on the mechanical response of composite laminates subjected to tensile, compressive, and shear loads. The conclusions reached by the authors suggest that the distribution and geometry of defects are important variables to consider in the production of composite material parts.

The initial studies investigating the effects of tow-drops were conducted by Blom et al. in 2009 [4], where the conditions under which these singularities appear have been described. The study simulated the variation of several factors, including the initial angular variation on the plate, tow width, staggering value, and the number of plies in the laminate. The experiment demonstrated that tow-drops can act as crack initiators and that the mechanical strength of the part is significantly weakened with the increase in the resin area created by the singularity.

Building upon the findings of previous research, Fayazbakhsh et al. (2013) [7] made a significant contribution to the understanding of these singularities by introducing the "Defect Layer Method." This method involves the incorporation of a percentage of defect material in the elements of the mesh (specifically resin for gaps and composite for overlaps). This approach enables a more accurate modeling of heterogeneities such as gaps and overlaps generated by tow-drops. The study demonstrates that the holes generated by singularities can reduce the buckling load capacity by 15%, whereas the configuration using overlaps to fill the holes will increase the mechanical strength of the part, but will result in thickness variations.

In 2014, Falcó et al. [8] published an article addressing the effects of tow-drops on the mechanical performance of parts manufactured by AFP. The article focused on the tensile strength of notched and unnotched specimens with and without tow-drops, demonstrating that failure would initiate at the holes and propagate along the resin zones. It was additionally observed that specimens with singularities introduced through staggering exhibited failure profiles that were strikingly similar to those without tow-drops.
Subsequently, in 2017, they published an article [9] presenting a numerical simulation model of a specimen containing tow-drops with and without a notch. Their model proved to be effective in predicting the effects of these singularities on the part, as well as the resulting failure modes, although it required significant computational and multiphysics modeling efforts.

Analysis of the aforementioned works reveals a clear interest in developing a numerical simulation model that can provide recommendations to assist designers dealing with tow-drops issues. This model should accurately predict the behavior of a part containing such singularities while being robust and fast enough to be used in a variety of scenarios encountered in industry. We thus propose a model simulating a singular line of tow-drops to isolate its effects and allowing to vary the geometry of the singularity to characterize its influence.

2. Description of the proposed tow-drop model

In this work, a ply scale model is constructed to provide a visual representation of the resin triangles formed by tow-drops with sufficient precision. A composite part is represented by a square flat plate measuring 300 mm on each side. The plate is divided into three zones. The first zone has the properties of the composite material oriented at 0°, representing the first nominal course deposited by the AFP machine. The second zone has the properties of the composite material oriented at $\Delta\alpha$, which is the angle of incidence between the two deposited courses. The last zone is located at the interface between the initial two zones and encompasses the resin triangles resulting from the collision of the two courses, consequently, it is assigned the mechanical properties of the resin.
To study the influence of resin zones, comparison of the mechanical responses to tensile loading between cases with and without resin pockets has been performed. The model without resin pockets (healthy case) has been programmed by filling the resin zones with composite material oriented at $\Delta\alpha$ instead, leaving only zones 1 and 2.

The HexPly AS4/8552 material has been selected, which mechanical characteristics are presented in Table 1 [9].

Table 1. HexPly AS4/8552 properties.

Hexply AS4/8552		
E_{11} = 137.8 GPa	E_{22} = 8.6 GPa	E_{33} = 8.6 GPa
ν_{12} = 0.35	ν_{13} = 0.35	ν_{23} = 0.487
G_{12} = 4.9 GPa	G_{13} = 4.9 GPa	G_{23} = 2.8 GPa
Epoxy resin		
E_m = 5.07 GPa	ν_m = 0.35	

On the plate, each resin pocket is represented by a triangle whose dimensions are controlled by the tow width and by $\Delta\alpha$, the angle of incidence between the courses. The model is illustrated on Figure 3. A single ply symmetrized $[0]_s$ was selected to establish a trend in the results, which can be further refined in a subsequent study where resin pockets are integrated into a composite stacking as traditionally manufactured.

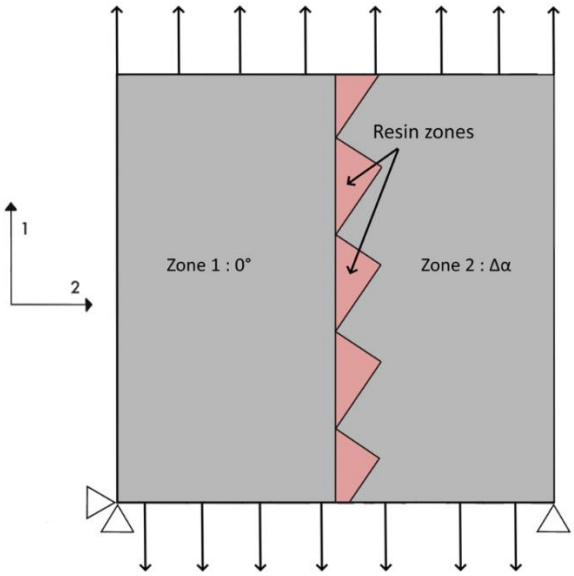


Figure 3. Schematic description of the studied tow-drop areas.

The model of the plate has been developed to allow for variation in the angle of incidence between the two courses. This model is intended to be integrated into a numerical computation routine using Abaqus© FE software. The plate has been meshed using S4R and S3R elements in order to represent the geometry of the singularities. An example of the mesh and associated stress results can be seen in Figure 4.

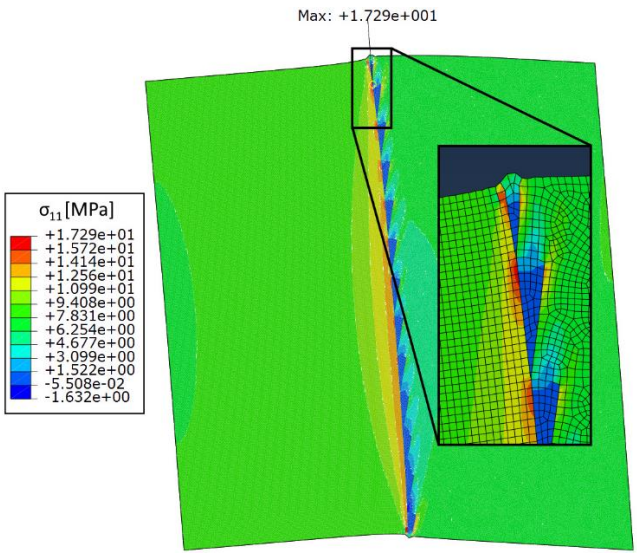
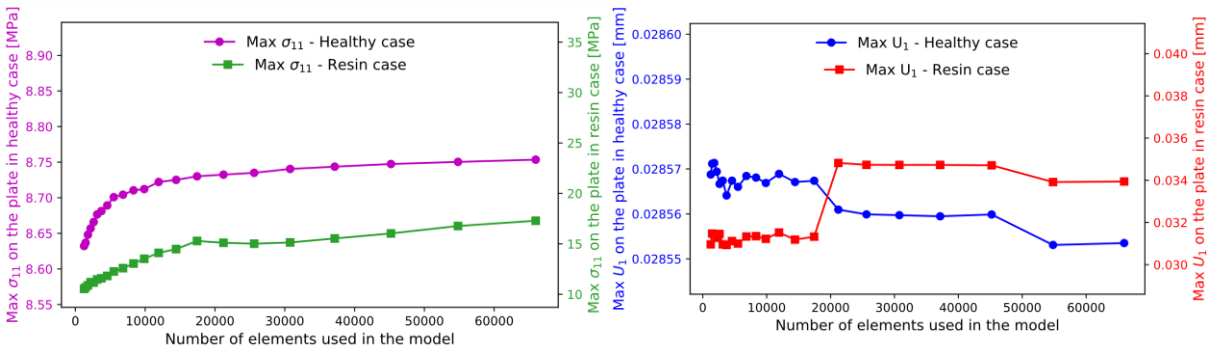


Figure 4. Meshing of the model and simulation results.

Tension is applied to the upper and lower edges of the model (*cf.* Figure 3). To simulate this tension, a nominal load of 4 MPa is imposed on both edges, with the objective of examining the stress distribution and deformations experienced by the plate. Figure 4 shows in the shape of the deformed part and the cartography of the stresses σ_{11} concentration on the plate after simulation. In this initial study, the computations will remain within the linear elastic domain of the material.

To ensure that the results were not influenced by the mesh quality, a mesh convergence study was conducted for both the model with singularities at an angle $\Delta\alpha = 5°$ and a healthy model, which is the ideal case where no resin pocket exists, leaving only zones 1 and 2. The convergence study was carried

out for two quantities of interest: maximal stress in the direction of tension (σ_{11}) on the plate, as well as the vertical elongation of the plate (max U_1). Results indicate that a minimum of 40,000 elements would guarantee a sufficient convergence of the studied quantities (Figure 5).



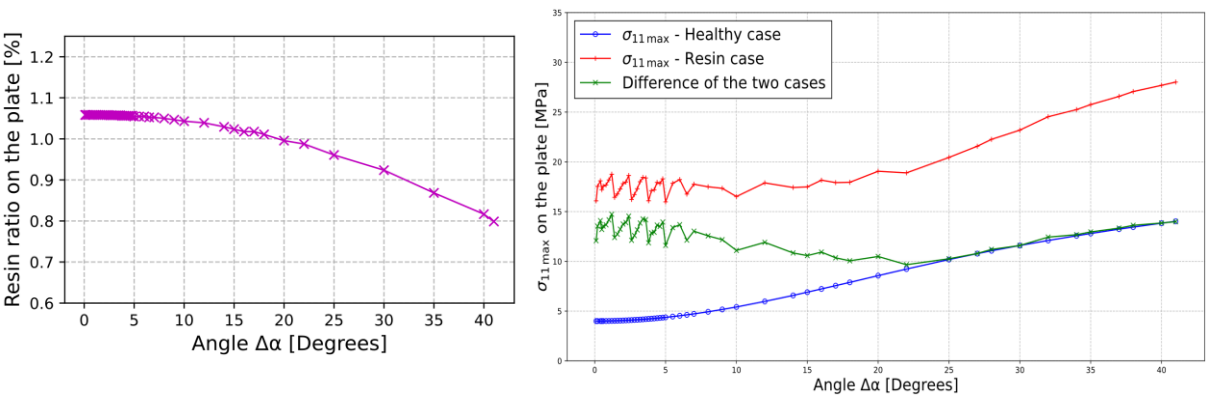
(a) (b)

Figure 5. Mesh convergence analysis of the model for (a) σ_{11} and (b) max U_1.

3. Simulations and results

Tow width has been set to 6.35 mm as it is an industrial standard. Angle of incidence $\Delta\alpha$ has been varied from 0.1° to 40°. This allowed to investigate the influence of resin pockets shape and configuration on the plate mechanical behavior. Further work could involve the straightforward integration of this type of program, with parametric or stochastic approaches to analyze the sensitivity of the model to different input parameters.

Figure 6 (a) depicts the resin ratio on the plate as a function of the angle of incidence, by dividing the area of the resin zones by the area of the plate. This ratio decreases by approximately 20 % as the angle of incidence increases from 0° to 40°, showing that the quantity of resin in the plate decreases as the angle $\Delta\alpha$ increases. Consequently, this resin quantity reduction is to be kept in mind when discussing the following results.



(a) (b)

Figure 6. (a) Area of resin pockets on the plate with respect to $\Delta\alpha$. (b) $\sigma_{11\,max}$ within the whole plate with respect to $\Delta\alpha$.

The results of the simulations are displayed on Figure 6 (a) for $\sigma_{11\,max}$ and Figure 7 for $\Delta U_{1\,max}$. Three curves can be observed in the graphs: resin case signify that the singularities on the model are filled with

the properties of neat resin, whereas on the healthy case, they are filled with the properties of composite oriented as in zone 2, at Δα°. The difference curve is obtained by subtracting the values of the healthy case from the values of the resin case. This curve isolates the effects of the singularities, as the effects of tows misalignment are subtracted.

The maximal stress σ_{11} on the plate highlights local stress concentrations. It is observed on the Figure 6 (b) that the maximal stress on the plate varies with the angle of incidence Δα. In the healthy case, $\sigma_{11\,max}$ increases steadily as Δα increases. In the resin case, $\sigma_{11\,max}$ remains almost constant up to Δα = 23° after which it rises significantly. The difference curve highlights that, as Δα grows, the resin-induced stress varies from three to two times the stress due to fiber misalignment. This behavior indicates that the resin causes a local stress concentration on the plate, particularly noticeable at higher misalignment angles. This result implies that resin pockets reduce the mechanical performances of the parts, with tow-drops areas acting as potential failure initiators.

$$\Delta U_{1\,max} = U_{1\,max\,final} - U_{1\,max\,initial} \tag{1}$$

The graph in Figure 7 shows the maximal vertical elongation ΔU_1 (see Eq. 1) as a function of the angle of incidence Δα. Both the healthy and resin cases demonstrate an increase in $\Delta U_{1\,max}$ with rising Δα. However, the resin case exhibits a significantly higher $\Delta U_{1\,max}$ compared to the healthy case, with values approximately twice as important. This indicates a global impact where the resin amplifies the elongation of the plate, suggesting that the resin contributes to the weakening of the properties of the part in the same magnitude as the fiber disorientation.

These results indicate that the influence of resin pockets is increasing as the angle of incidence grows, despite the decrease of overall resin quantity (*cf.* Figure 6 (a)).

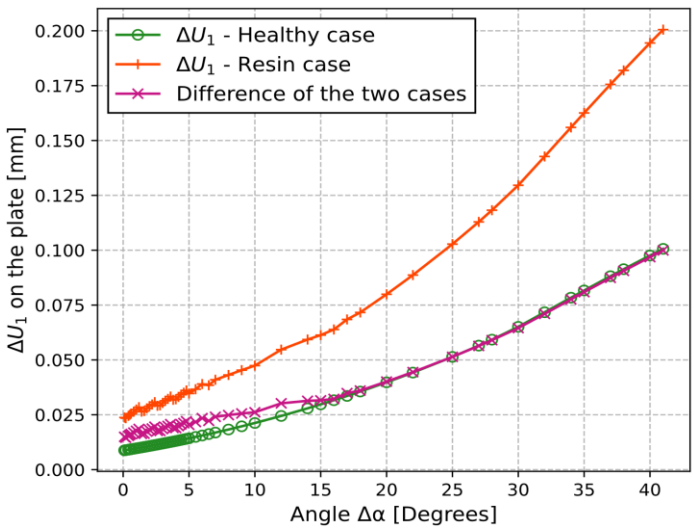


Figure 7. Maximal vertical elongation (ΔU_1) of the plate for resin and healthy cases and their difference as a function of Δα.

5. Conclusions

This study presents a comprehensive investigation into the impact of resin pockets resulting from tow-drops in Automated Fiber Placement (AFP) process on the mechanical behavior of composite plates in tensile loading. By modeling and varying the geometry of these resin zone, this research isolates and evaluates their impact on the mechanical properties of composite parts.

The research highlights the necessity of comprehending tow-drop linked singularities in composite manufacturing processes, which can compromise the structural integrity of manufactured parts. Various solutions for addressing tow-drops were explained, with a focus on the full gap approach due to its preference in industrial applications.

A composite plate model with embedded triangular resin pockets caused by tow-drops has been developed. Implemented in Abaqus©, this model varies the angle of incidence ($\Delta\alpha$) between adjacent fibers to analyze the effects on stress distribution and deformations. This approach allows for a detailed simulation of how these resin pockets influence mechanical behavior under tensile loading.

Simulations reveal that resin pockets lead to increased stress concentrations and elongation, growing with the angle of incidence $\Delta\alpha$. For instance, the resin pockets double the vertical elongation of the plate compared to a configuration without tow-drops. The maximal stress σ_{11} is approximately constant until $\Delta\alpha$ reaches 23°, beyond which it surges significantly. These results underscore that resin pockets can have a significant effect on mechanical performance, and thus, design strategies should account for them to optimize composite parts.

Further research could be conducted to enhance the model by incorporating additional loading modes, such as compression and shearing, and by modelling more plies in the stacking. Additionally, the results obtained from the simulation could then be validated through an experimental study.

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