Experimental and numerical characterization of the in-plane mechanical properties of interlaced composites

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1 Abstract

Recent developments n automated fiber placement technology have facilitated the production of quasi-woven composite laminates. These so called interlaced laminates offer improved impact tolerance while retaining the strength and stiffness of conventional angle-ply composites. In this study, the in-plane tensile behavior of these types of laminates was characterized experimentally and numerically. The interlacing process was found to minimally affect laminate stiffness, while the effect on laminate strength was dependent on the layup. The numerical modeling approach, employing a multiscale homogenization framework to capture the effect of the through thickness undulations, was found to provide good predictions of laminate stiffness and strength, and correctly predicted laminate failure modes.

2 Introduction

Composites are particularly susceptible to delamination damage from low-velocity out-of-plane impact loading. Arguably, this is one of the primary factors preventing the further use of composites for primary aerospace structures [1]. Existing methods to improve the impact tolerance of composites e.g. 3D weaving or z-pinning, have deleterious effects on the undamaged in-plane mechanical properties of a laminate, and are often incompatible with the automated manufacturing techniques used in the aerospace industry. Recently, a novel preforming method known as interlacing has been developed, which harnesses the precision and flexibility of automated fiber placement (AFP) machines to produce pseudo-woven laminates. The through thickness fiber connectivity of these interlaced laminates improves their impact tolerance while minimally affecting their undamaged in-plane strength and stiffness [2].

To manufacture an interlaced laminate, some of the "channels" on an AFP head are left empty, leaving gaps between the tows placed in a single pass. The size of the gap depends on the number of tows "skipped". After placing tows in a particular orientation the AFP head will place tows in all the other desired fiber orientations, before filling in the gaps left between tows in previous steps (Figure 1).

In this study, the in-plane tensile strength and stiffness of two different interlacing configurations are studied experimentally and numerically. The mechanical properties of the interlaced composites are compared with conventional non-interlaced laminates to quantify the effect of the interlacing process on the undamaged in-plane strength and stiffness of the laminates.

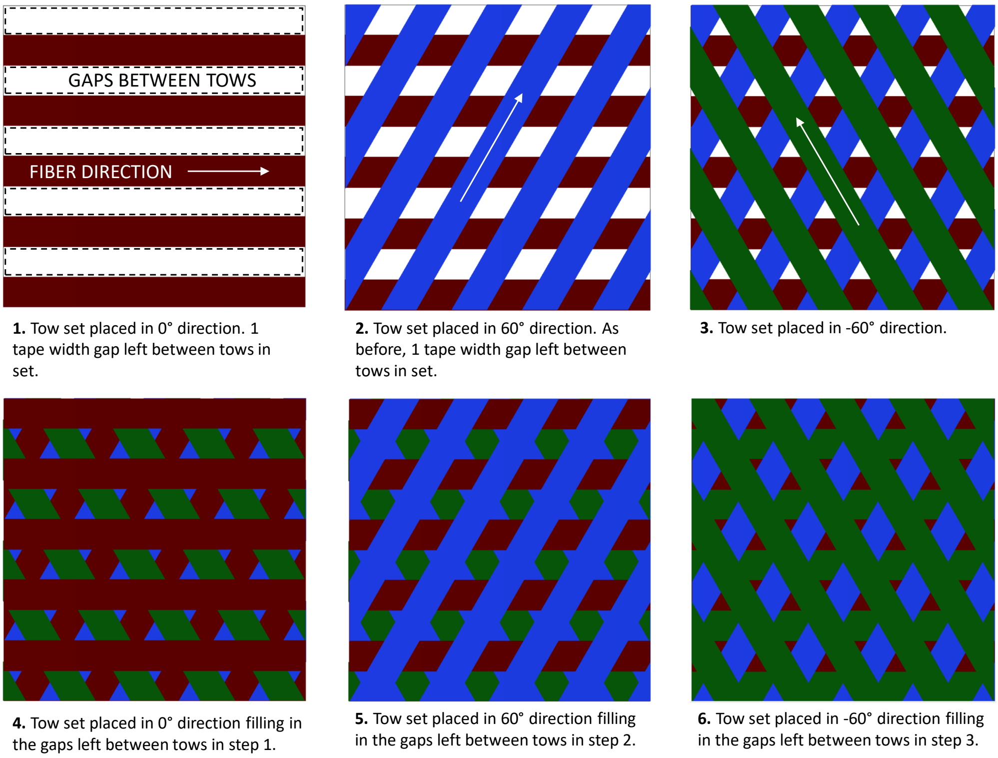

Figure 1: Schematic of the layup process for an interlaced laminate with 0°, 60°and -60°tows.

3 Experimental Characterization

Two different interlaced laminates were manufactured, one with 0°and 90°plies (XP_{int}), and one with 0°, 45°, 90°, and -45°plies (QI_{int}). In both laminates a gap of three tow widths was left between tows placed in the same pass. In addition, two reference - non interlaced - laminates were manufactured for comparison with the interlaced panels, (XP_{ref} and QI_{ref}). All laminates were manufactured using SHD Composites VTC401 prepreg, and were cured in a hot press at 120°C under 4 bars of consolidation pressure. Glass fiber end tabs were adhered to the specimens using an epoxy adhesive film. Specimens dimensions were chosen to ensure a representative volume of each configuration was tested. Six specimens of each configuration were tested to failure in a 300kN MTS universal testing machine. Strain measurements were taken using digital image correlation (DIC).

4 Numerical Modeling

Interlaced composites have intricate internal architectures whose complexity increases as the number of unique tow orientations in a laminate rises. In addition, due to the width of the tapes/tows used to manufacture these laminates, the representative volume elements (RVE) of these materials can be very large, or may not exist at all. Existing software packages for the creation of textile composite geometries (e.g. TexGen or WiseTex) are unable to efficiently create the geometries of interlaced laminates. A novel multiscale modeling methodology was developed in this study in which the effect of the through thickness tow undulations is captured by the modification of material properties in regions containing tape undulations. Compared with conventional modeling strategies in which curved tow paths are modeled geometrically as solid continua, the new method reduces the geometric complexity of the finite element models, reducing computational cost and eliminating mesh interpenetration. The approach is illustrated in Figure 2.

Damage is modeled using a 3D continuum damage mechanics framework. Damage initiation is predicted by the 3D failure criteria developed at Northwestern University [3]. After the onset of damage,

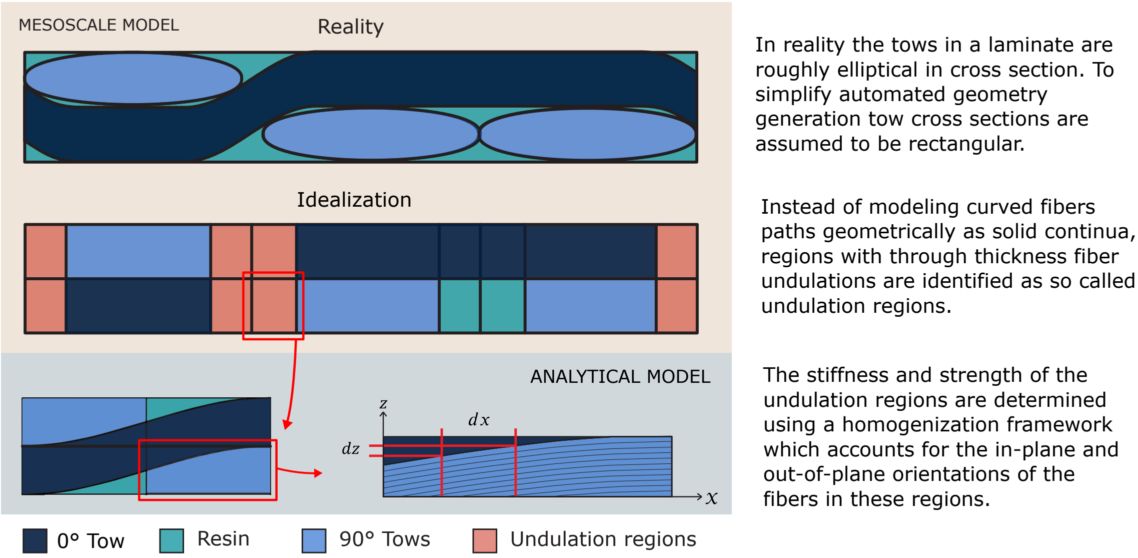

Figure 2: Schematic of the interlaced laminate geometry idealization

Table 1: Experimental and numerical stiffness and strength of interlaced laminates and their reference configuration.

Configuration	Experimental		FEA	
	Modulus (GPa)	Strength (MPa)	Modulus (GPa)	Strength (MPa)
XP_{ref}	61.30 $\pm$ 1.17	1311.28 $\pm$ 59.21	-	-
XP_{int}	62.83 $\pm$ 4.31	1060.31 $\pm$ 47.54	64.90	941.01
QI_{ref}	43.92 $\pm$ 0.88	654.66 $\pm$ 32.01	-	-
QI_{int}	43.10 $\pm$ 0.74	705.67 $\pm$ 28.85	46.28	646.01

the stiffness of the material is degraded according to a set of damage evolution laws adapted from the work of Maimi *et al.* and Liu *et al.* [4][5].

5 Results and Discussion

The results of the experimental and numerical characterization of the interlaced laminates are summarized in Table 1. The stiffness and strength of the interlaced quasi-static laminate are within 1.8% and 7.7% of the reference configuration. The higher strength of the interlaced configuration is theorized to result from the consolidating effect of the through thickness reinforcements, which prevent the formation and propagation of delamination and thus delay pull-out failure of the specimens. The stiffness of the interlaced cross ply laminates is 2.5% lower than the reference configuration, which is a marginal reduction and within the experimental variation. There is however, a relatively large discrepancy between the interlaced and non-interlaced cross-ply strengths of 19.1%. This discrepancy can be partly attributed to stress concentrations resulting from high clamping pressures in the grips. Due to the large non-standard width of the interlaced specimens, significant loads were required to fracture the specimens, and as a result, high clamping pressures were applied to prevent slippage of the specimens during testing. In addition, since cross-ply laminates generally fail through fiber fracture rather than delamination, the stress concentrations resulting from the fiber undulations may reduce the strength of the laminate relative to non-interlaced composites.

Numerical model predictions are in reasonably good agreement with the experimental results. Laminate stiffness and strength are within 3.28% and 11.25% of the experimental values for the cross-ply configuration, and 10.7% and 8.45% for the quasi-isotropic configuration. Failure modes are consistent with experimentally observed failure sequences, with final failure of the specimens triggered by stress concentrations occurring at through thickness fiber undulations, see Figure 3.

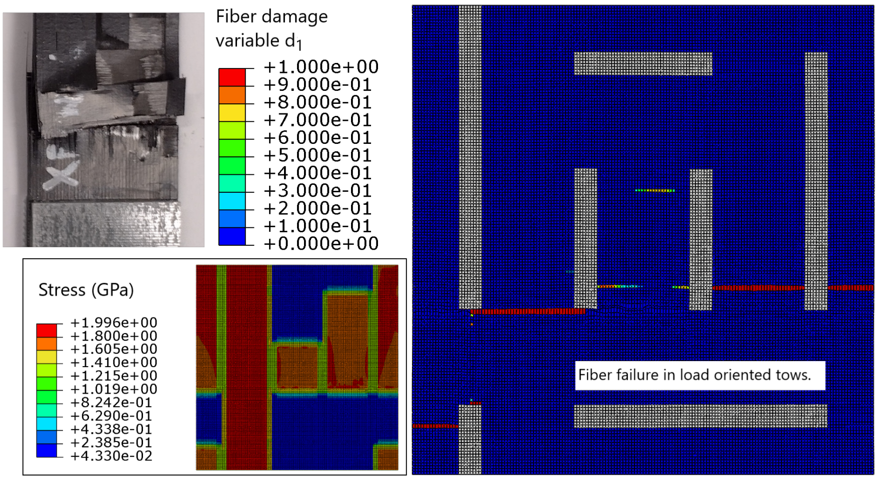

Figure 3: Numerical prediction of longitudinal fiber failure in the cross-ply interlaced laminate. Fiber failure is predicted to occur at the locations of through thickness fiber undulations as observed experimentally.

6 Conclusions

The response of interlaced laminates to in-plane tensile loading was explored. The effect of interlacing on laminate stiffness was found to be negligible, with a maximum discrepancy between interlaced and non-interlaced laminates of 2.5%. In quasi-isotropic laminates, the interlacing process was found to provide a marginal increase in strength, possibly due to the effect of the through thickness fiber connectivity on delamination formation and propagation. In cross-ply laminates, interlacing was found to reduce laminate strength. The numerical modeling methodology developed in this study was found to effectively capture the stress concentrations resulting from through thickness fiber undulations and their effect on the failure sequence of the laminates. Predictions of stiffness and strength were within 10.7% and 11.25% of the experimentally observed values respectively. Future studies will focus on the response of interlaced laminates to impact loading.

References

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