SPATIAL FIBER VOLUME FRACTION QUANTIFICATION OF CORE-SHELL STRUCTURED THERMOSET TOW-PREGS

Maximilian Pitto, (Ph.D.M.E.)[3], Shaharear Md. Emtiaz, (Ph.D.M.E.)[2], Prof. Suresh G. Advani[1,2]
University of Delaware I Center for Composite Materials[1] I Department of Mechanical Engineering[2] I University of Auckland, Department of Mechanical and Mechatronics Engineering[3]

Introduction

Deng et al. [1] have demonstrated the self-supporting capabilities of a rapid interlayer curing assisted continuous carbon fiber-reinforced thermoset additive manufacturing process. A cartoon of the process is illustrated in Figure 1.

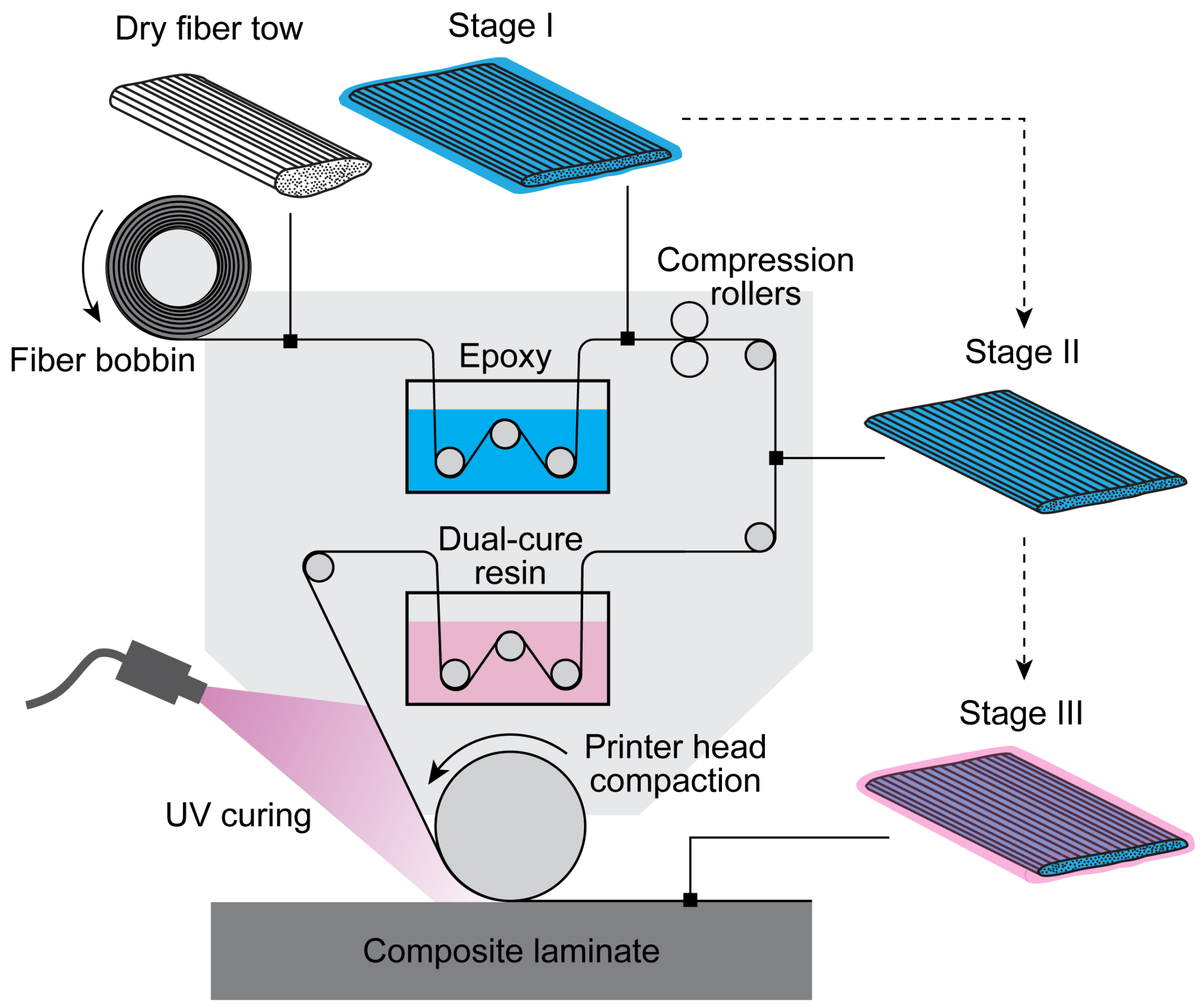


Figure 1: Schematic illustrating the impregnation and dual-cure resin coating process for continuous carbon fiber additive manufacture. UV resin and epoxy are admixed in the dual-cure resin bath. The tow-preg coating is partially cured by UV LEDs prior to compaction.

Tow-preg stages of interest are:

- Stage I: epoxy impregnated
- Stage II: surplus resin removed (metered)
- Stage III: consolidated dual-cure coated

Objectives

- Linearly replicate the printing process for controlled impregnation, coating and simplified sample extraction
- Quantify effect of pre-tension and metering orifice thickness on fiber volume fraction at stages I and II by cross-sectional microscopy image processing
- Qualitatively inspect the UV coating uniformity at stage III by cross-sectional microscopy image processing

Experimental setup

Figure 2 depicts a linear replica of the additive manufacturing process in Figure 1. This setup enabled precise sample extraction at each process stage.

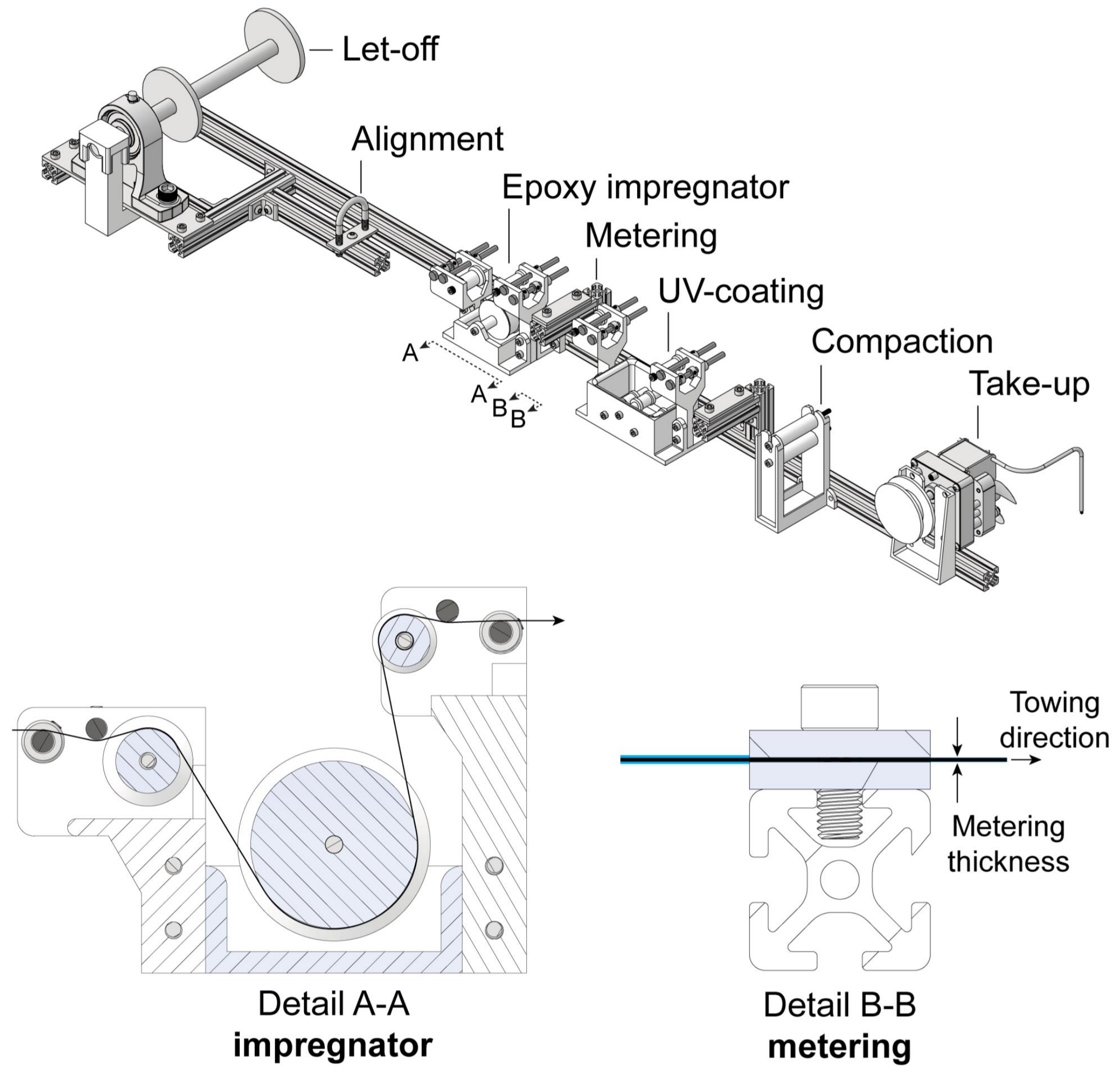
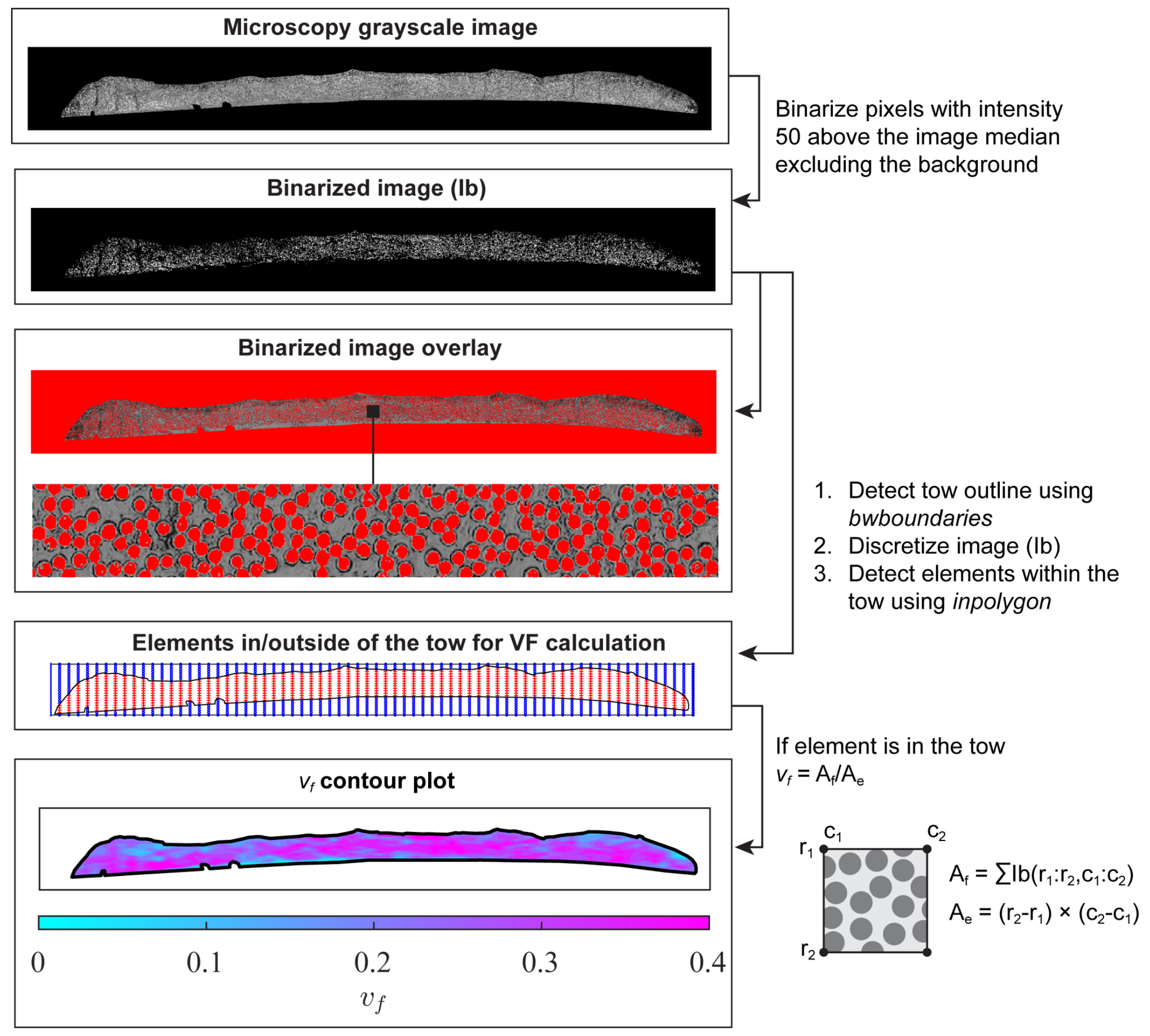


Figure 2: CAD drawing of the experimental setup. The linear process actuated by a constant-speed motor enabled precise sample extraction between process stages. Details A-A and B-B illustrate the impregnator and metering device, respectively.

Image processing workflow

The fiber cross-section analysis workflow by MATLAB image processing is depicted in Figure 3.



Binarize pixels with intensity 50 above the image median excluding the background

1. Detect tow outline using *bwboundaries*
2. Discretize image (Ib)
3. Detect elements within the tow using *inpolygon*

If element is in the tow $v_f = A_f/A_e$

$A_f = \sum Ib(r_1{:}r_2, c_1{:}c_2)$

$A_e = (r_2-r_1) \times (c_2-c_1)$

Figure 3: Spatial quantification of the fiber volume fraction by MATLAB image processing. The images were binarized and discretized, followed by outline detection and classification.

Discretization sensitivity

The tow cross-section was divided into 75, 675, 1200, and 1875 cells. The fiber volume fraction (v_f) sensitivity to discretization is seen in Figure 4. The mean v_f changed by 0.6% between the two finest meshes. Subsequent results utilize the 1200 grid.

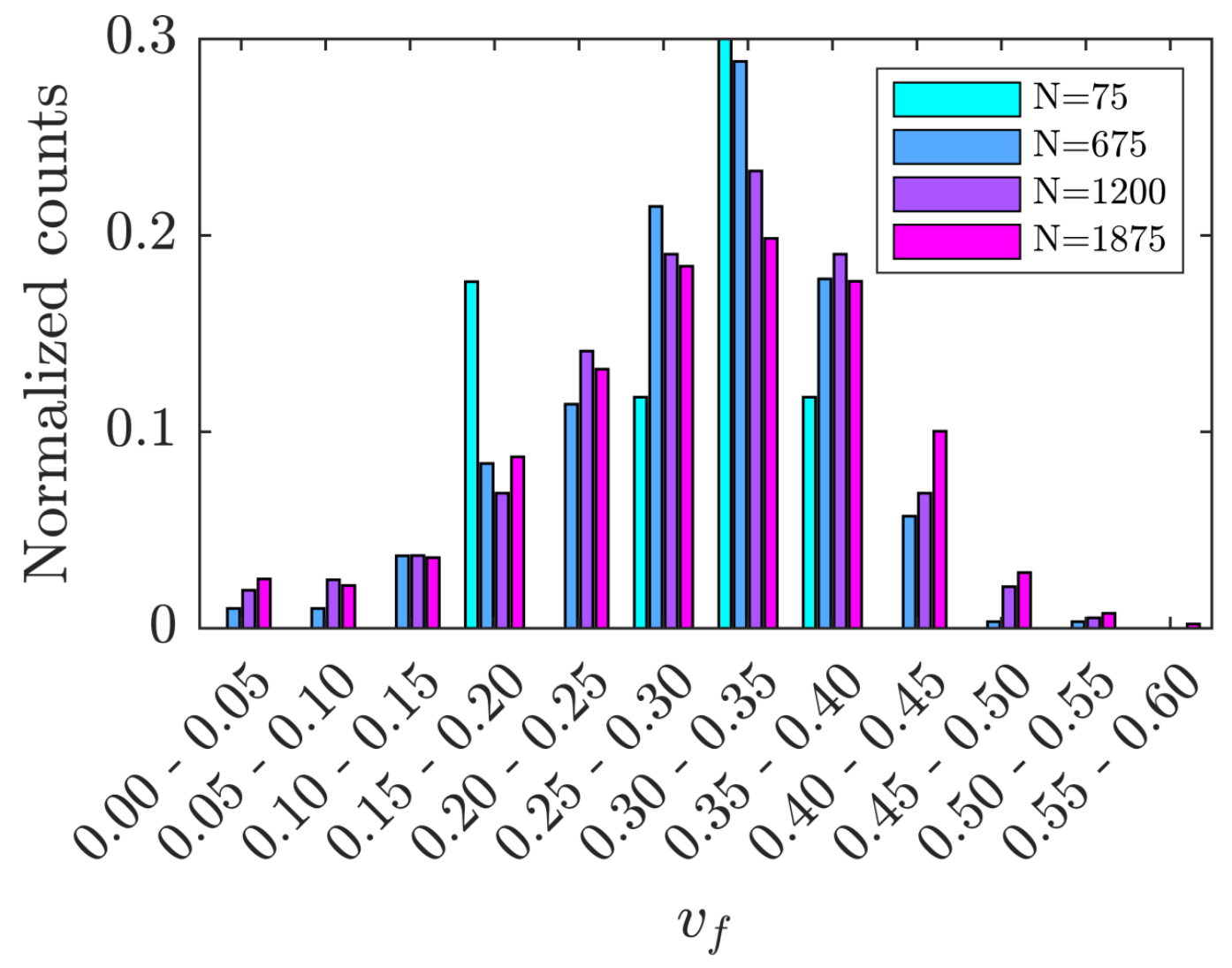


Figure 4: Fiber volume fraction histogram for four discretization densities. With decreasing cell size the distribution flattens but the mean remains steady.

Stage I – Pre-tension

Pre-tension had a negligible affect on the fiber distribution (Figure 5 a-c). However, the void content in 5 mm × 15 mm specimens measured by micro computed tomography reduced with increasing tension (Figure 5 c).

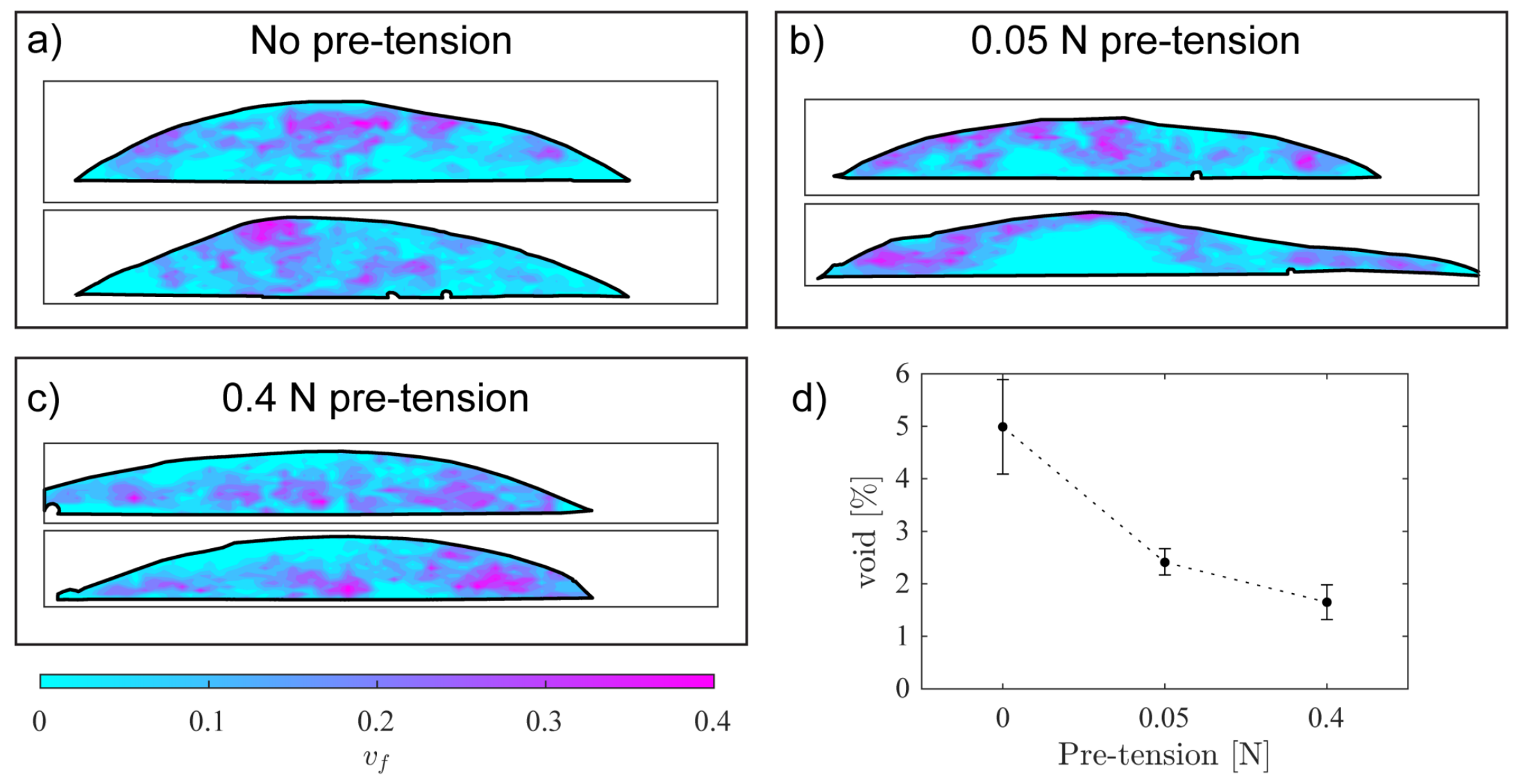


Figure 5: (a-c) Cross-section fiber volume fraction contour plots and (d) void content measured by mCT at stage I for three pre-tensions applied at the fiber bobbin.

Stage II – Metering orifice thickness

A high and homogeneous fiber volume fraction was attained by metering with an orifice thickness of 120 μm (Figure 6 and 7).

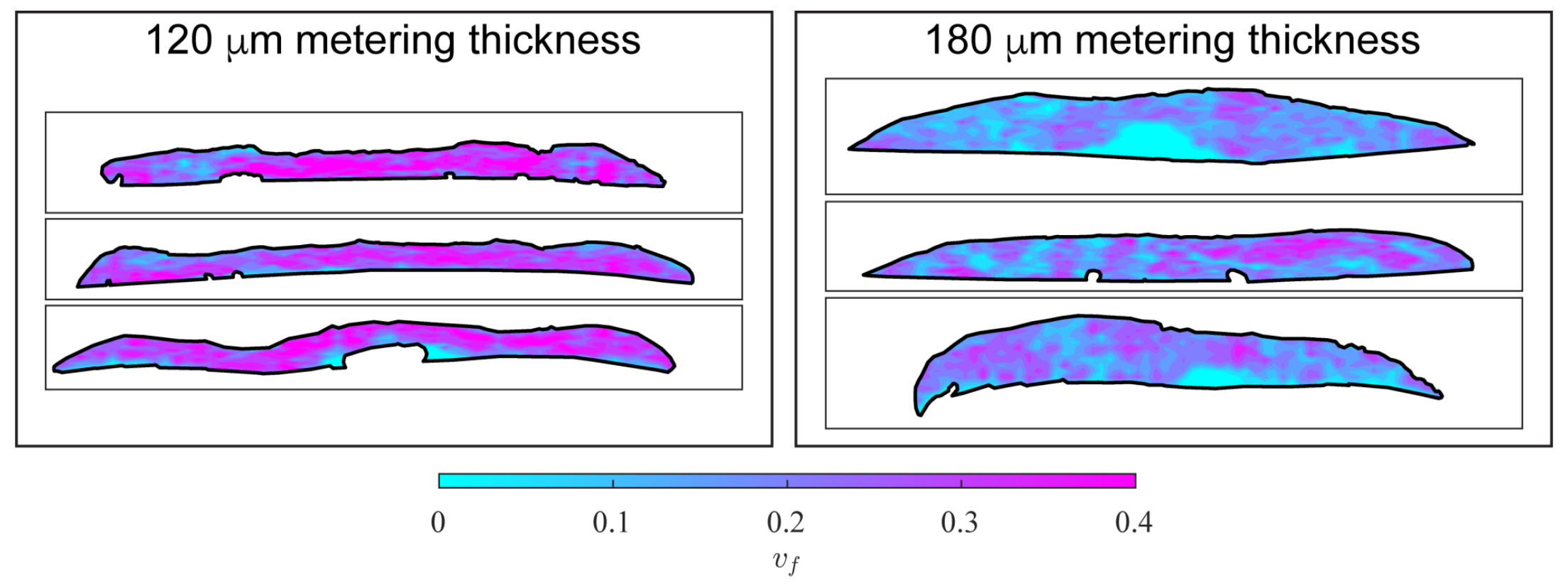


Figure 6: Tow cross-section fiber volume fraction contour plots at stage II with no pre-tension for a metering thickness of 120 and 180 μm, respectively.

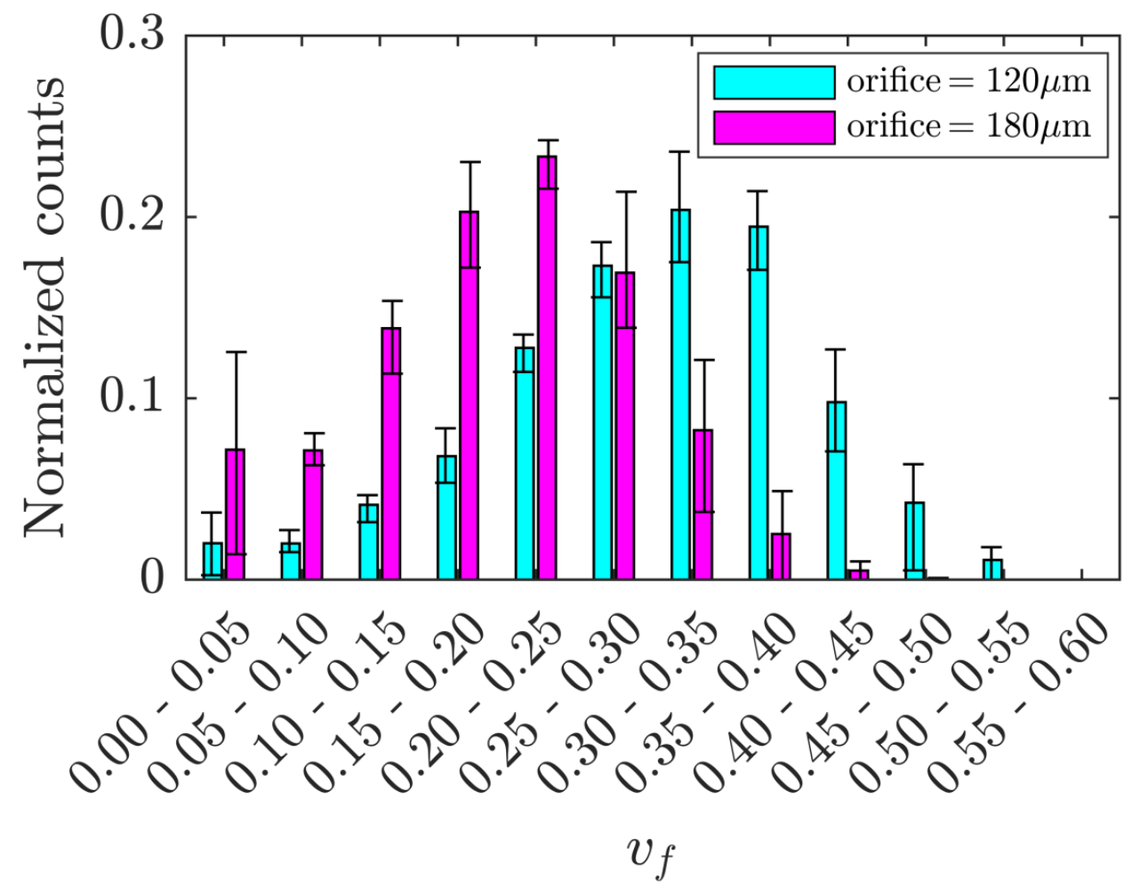


Figure 7: Fiber volume fraction histogram of the epoxy impregnated tow at stage II. A metering orifice thickness above 120 μm produced resin rich defects seen by the counts in 0-0.1 bins.

Stage III – UV resin coating variability

UV resin coating followed by metering through a 240 μm orifice produced variable samples. The second specimen in Figure 8 had a uniform thickness because it picked up UV resin exceeding the orifice thickness. Specimens 1 and 3 were thinner than the orifice.

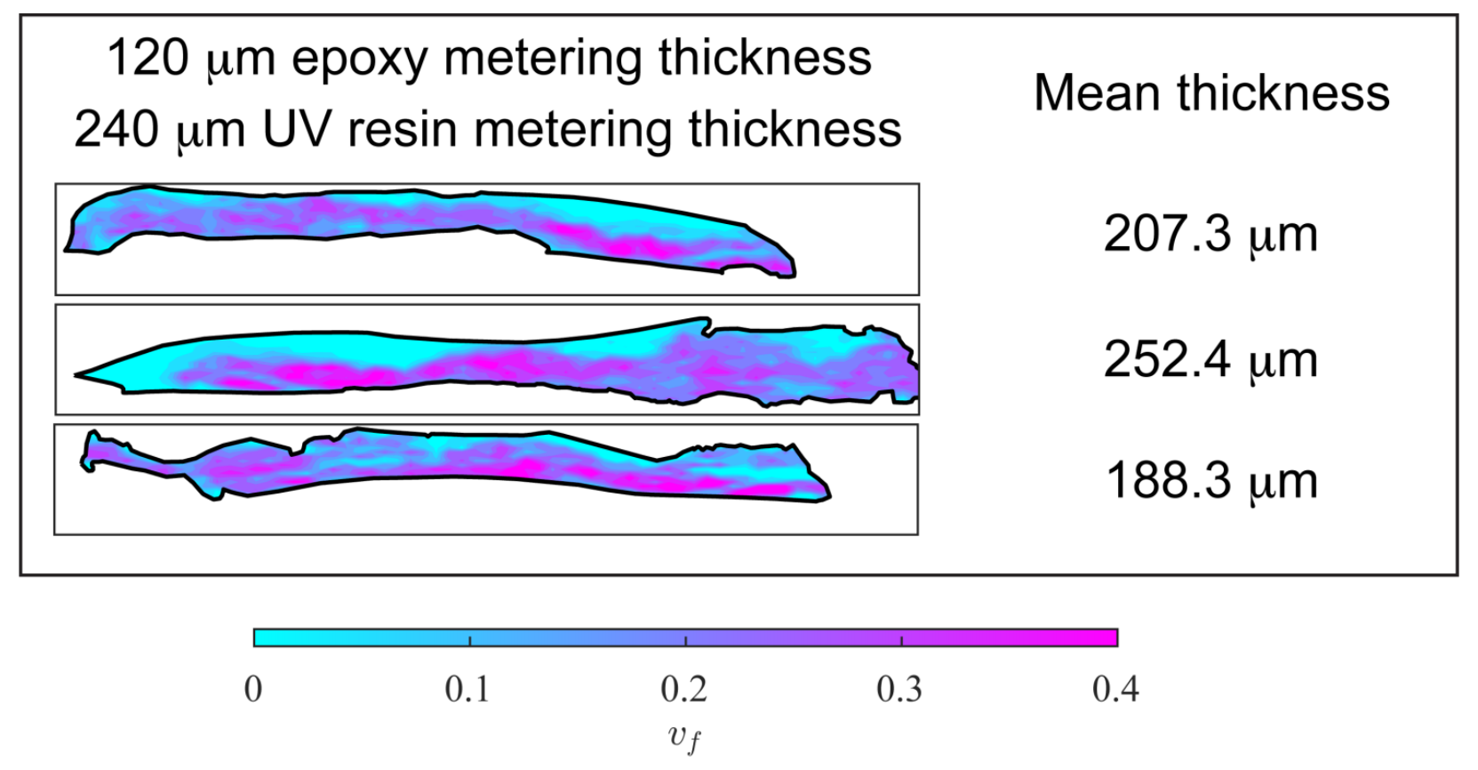


Figure 8: Tow cross-section fiber volume fraction contour plots at stage III with no pre-tension for an epoxy and UV resin metering thickness of 120 and 240 μm, respectively.

Conclusions

- Stage II metering with a 120 μm gap uniformly and tightly packed the tow ($v_f = 0.30 \pm 0.02$)
- Stage III metering through a 240 μm orifice did not produce a uniform thickness

Future Work

- Improve stage III quality by reducing the orifice thickness. If ineffective, implement roll coating
- Representative global fiber volume fraction and void content will be measured by ASTM D3171 – 22 and D2734, respectively

Acknowledgements

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References

[1] Deng, Kaiyue, et al. "Core-shell structured tow-pregs enabled additive manufacturing of continuously reinforced thermoset composites." (2024)