ROLE OF FIBER CLUSTERS ON VOID FORMATION FOR ADDITIVELY MANUFACTURED CONTINUOUS CARBON FIBER THERMOSET COMPOSITES

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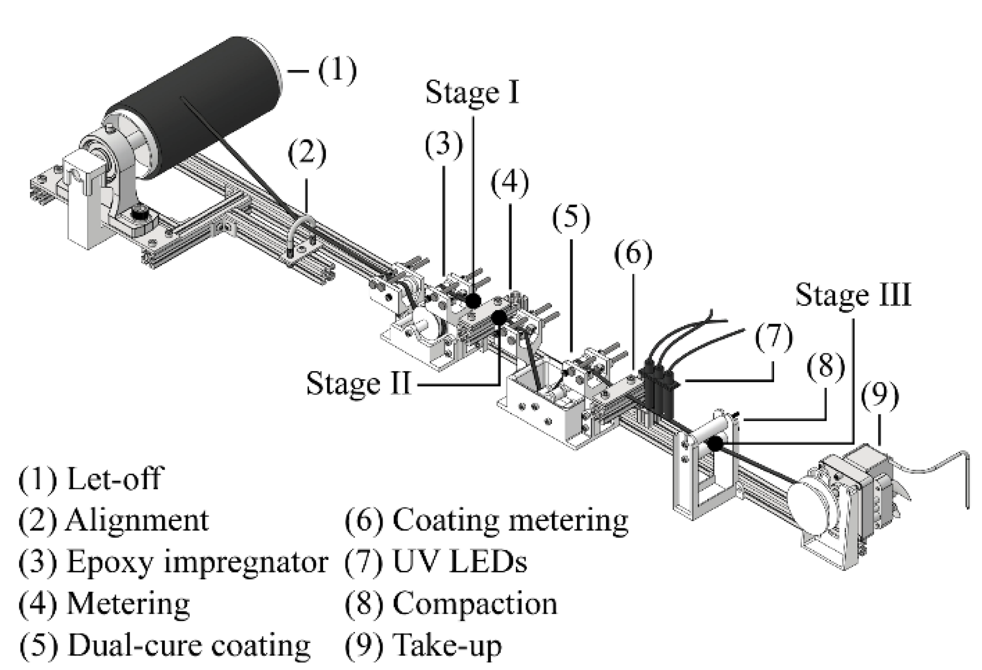
Introduction

- Additive manufacturing of continuous carbon fiber thermoset composites has led to the achievement of in-situ resin impregnation of dry carbon fiber tow with a wide range of thermoset resins saving processing time and storage consumptions of prepregs without affecting the mechanical properties.
- But voids inside the final 3d printed parts due to improper impregnation can significantly affect the final part quality which is highly undesirable. One big factor for improper impregnation can be defects in fiber tow geometry that alters the permeability of the tow.
- Void content was measured at various stages, (i.e., **Stage I** after first epoxy impregnation, **Stage II** after metering and **Stage III** after the final compaction at the printer head). The samples were cured to conduct micro-CT analysis and characterize the void content. Average void percentages after stage I, II and III were found to be 6%, 4% and 3% respectively.



Drawing of the experimental setup for epoxy impregnation, metering, dual-cure coating, and consolidation. The dry fiber tow is impregnated with epoxy. Metering device removes surplus epoxy resin between stages I and II. The epoxy-impregnated tow is then coated with a UV and epoxy resin admixture, which is cured and compacted by the printer head, leading to the final towpreg conformation at stage III [1].

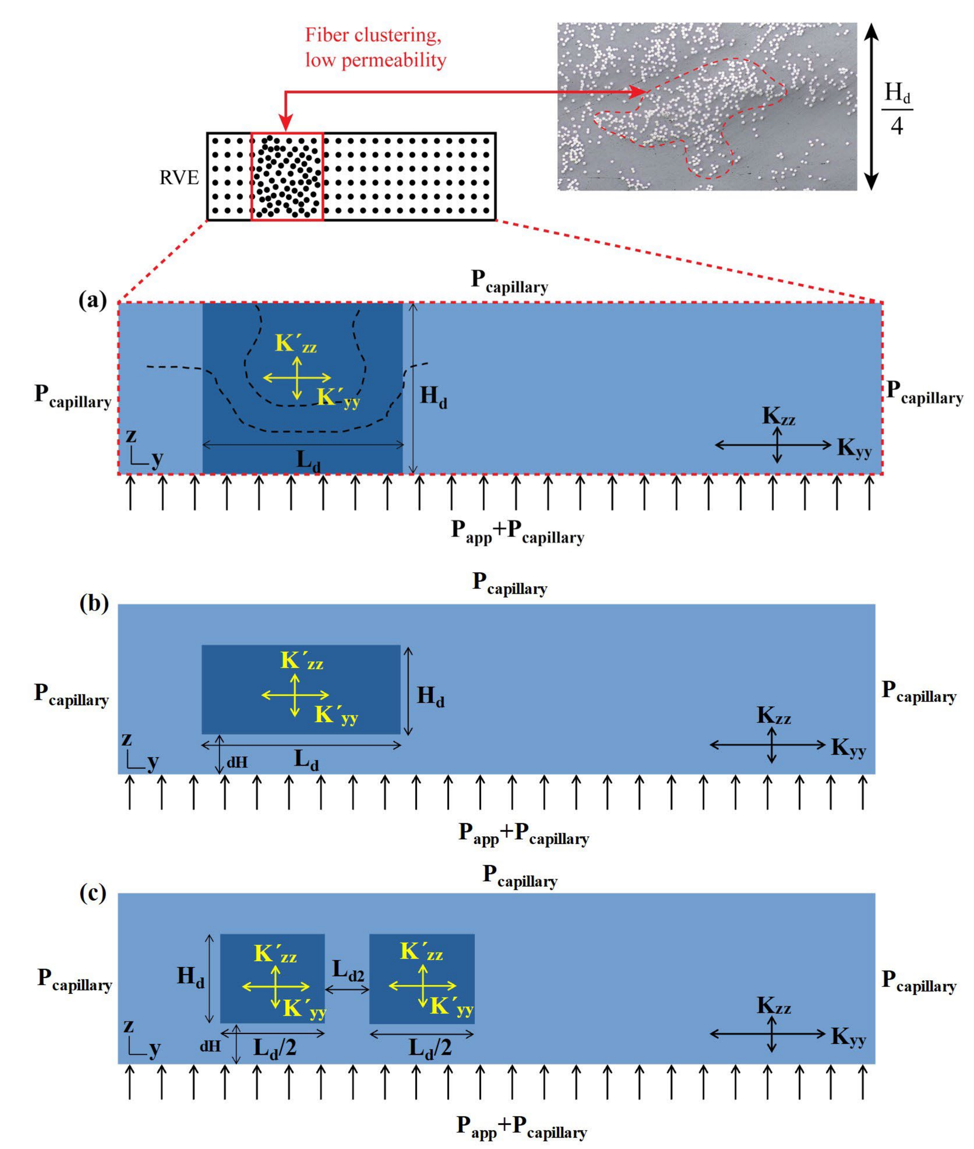
Objectives

- Develop models to uncover important material and process parameters that influence void formation
  - Fiber cluster effect on void formation

Model Formation

Fiber cluster effect on void formation

A model is developed to study the effect of heterogeneous permeability due to fiber clustering by introducing lower permeability zone was introduced inside a rectangular domain representing the cross-section of a fiber tow. Main goal of this study is to predict the resin impregnation and final void content based on permeability variation caused by fiber clustering, a defect in fiber tow geometry. The flow was assumed to be 2D, and resin flow follows Darcy's Law.



c_1 = Permeability reduction factor, L_d = length of the low permeability region (mm), dH = distance between the injection point and the low permeability region (mm), K = permeability (m^2), P = Applied pressure (Pa). Permeability value was calculated using Bruschke and Advani equation [2]

$$\frac{K}{r^2} = \frac{1}{3}\frac{\left(1-L^2\right)^2}{L^3}\left(3L\tan^{-1}\frac{\sqrt{\frac{1+L}{1-L}}}{\sqrt{1-L^2}}+\frac{L^2}{2}+1\right)^{-1}$$

Where, $L^2 = 4V_f/\pi$ and r is the fiber radius. Clusters are modeled as localized regions of significantly lower permeability, where c_1 is the permeability reduction factor.

$$k'_{yy} = c_1 \cdot k_{yy}$$
$$k'_{zz} = c_1 \cdot k_{zz}$$

The average Fiber volume fraction inside the 2D domain is conserved as follows,

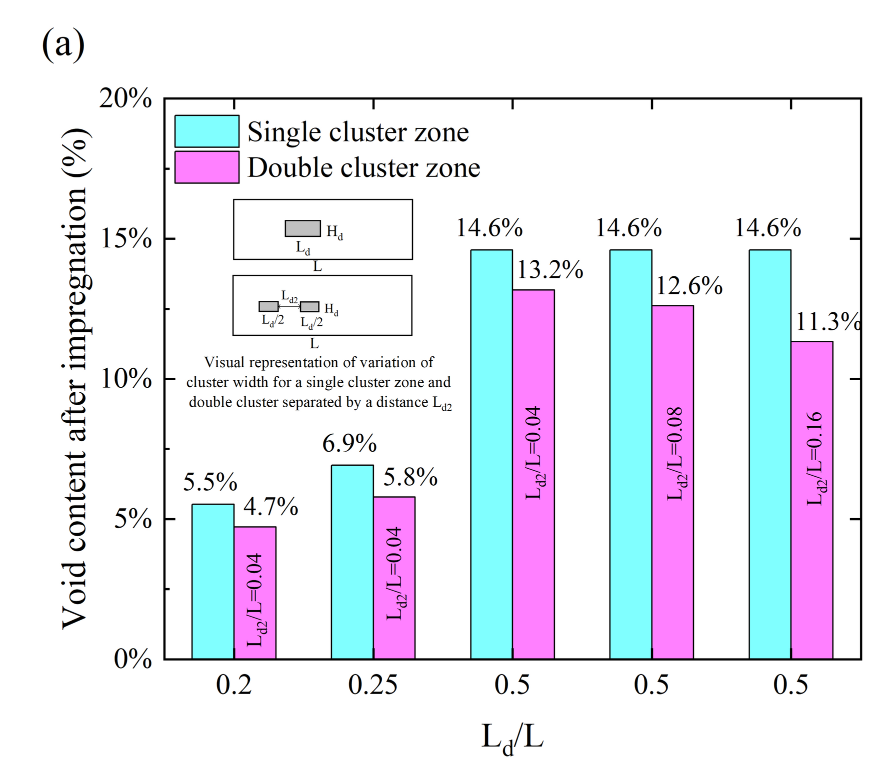
$$V_{f,avg} = A_{Cluster} \times V_{f,cluster} + A_{rest} \times V_{f,rest}$$

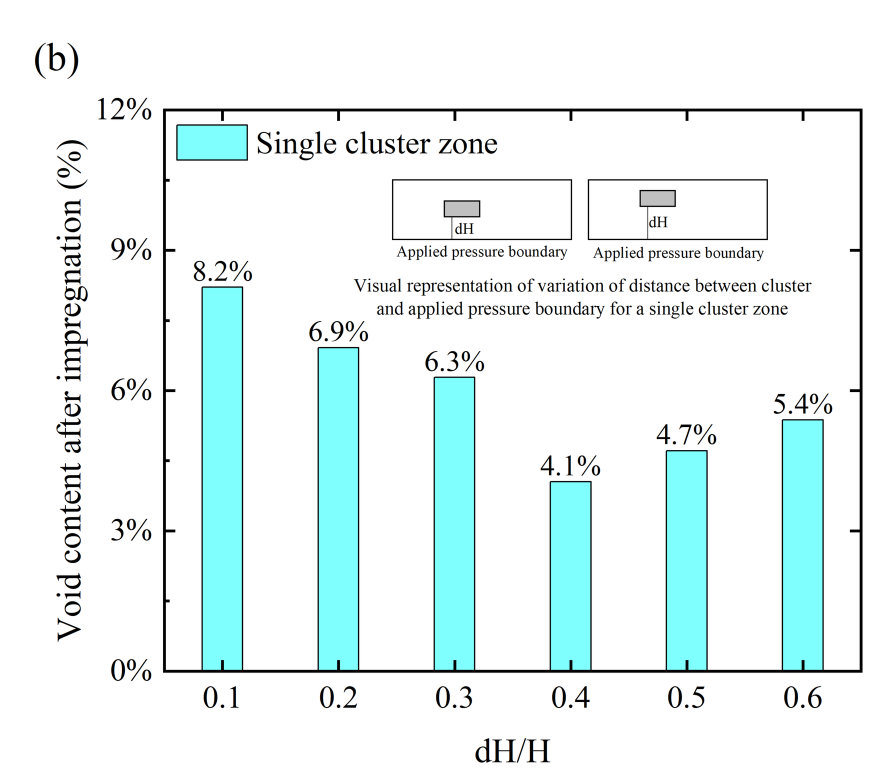
Results and Discussion

Void content sensitivity with respect to the normalized cluster width (L_d/L) and the permeability reduction factor (c_1) was studied. Relationship between these parameters is summarized in the following Table. For a constant cluster area (H_d decreases as L_d increases), the void entrapment increases with increasing cluster width.

Normalized cluster width, L_d/L	Cluster area (% of the total domain)	Permeability reduction factor, c_1 ~0.05	~0.1	~0.25	~0.5
0.05	5%	1.93%	1.54%	1.10%	0.24%
0.1	10%	4.63%	3.62%	2.34%	1.66%
0.15	15%	7.10%	5.24%	3.36%	1.84%
0.2	20%	9.73%	6.82%	4.74%	2.00%

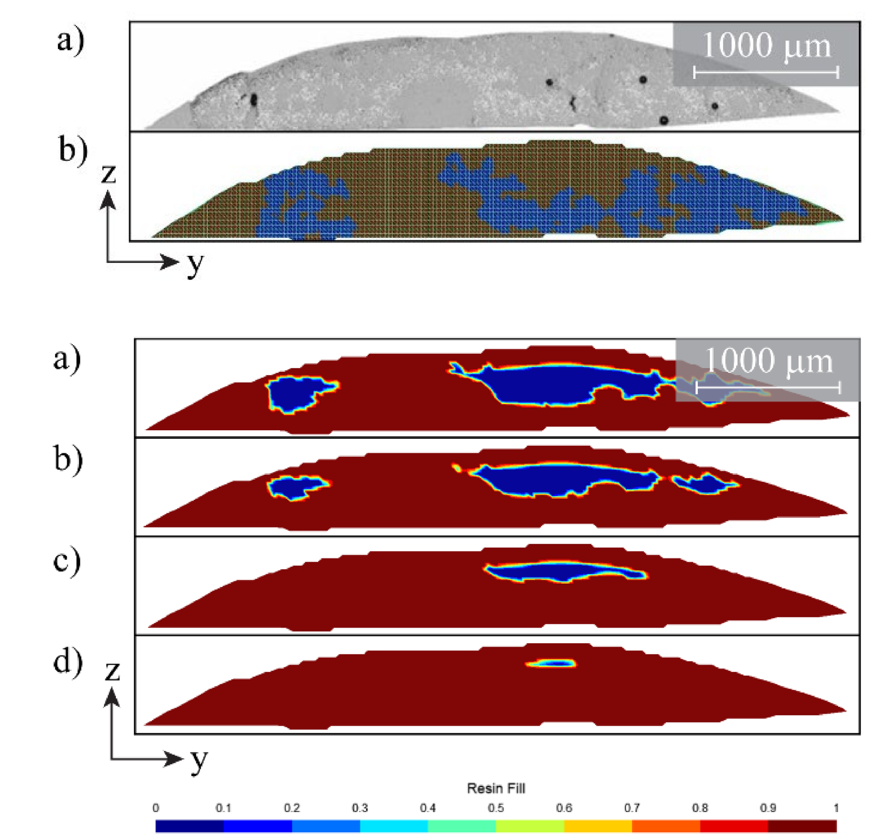
Effect of multiple clusters and different cluster location was also studied. For same normalized cluster width (L_d/L) but divided into two zones, void entrapment was reduced compared to a single zone. Cluster impact on impregnation is minimized when the normalized cluster zone separation (L_{d2}/L) increases. As the cluster distance from the applied pressure boundary increases, resin flow is less distorted, thereby reducing void entrapment.





Experimental Validation

Realistic tow geometry was used as the domain by detecting outlines of clusters from to implement them as regions of lower permeability in the clustering model. Final void content with permeability reduction factors of 0.25 and 0.5 show close correspondence with the experimental void content (approximately 4%-6%) after stage I.



Stage I impregnation modeling result for the geometry created from cross-sectional microscopy. The permeability reduction factor was (a) c_1= 0.05 (b) c_1= 0.1 (c) c_1= 0.25, (d) c_1= 0.5.

Learnings from the Model

Larger variability in permeability, fiber clustering length and clustering closer to injection leads to higher void content.

References

[1] Shaharear Md Emtiaz, Maximilian Pitto, Pavel Šimáček, Suresh G Advani, Role of fiber clustering and resin bleeding on voids and evolution of fiber volume fraction for additively manufactured continuous carbon fiber thermoset composites with dual-cure resins, Composites Part A: Applied Science and Manufacturing, Volume 189, 2025, 108601, ISSN 1359-835X, https://doi.org/10.1016/j.compositesa.2024.108601.

[2] M. V. Bruschke and S. G. Advani, "Flow of generalized Newtonian fluids across a periodic array of cylinders," *J Rheol (N Y N Y)*, vol. 37, no. 3, pp. 479–498, May 1993, doi: 10.1122/1.550455.

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