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Effect of reinforcement areal weight on laminate thickness in unidirectional carbon fiber reinforced composites

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Abstract

Carbon fiber–reinforced plastics (CFRPs) are extensively utilized in aerospace, defense, automotive, and marine applications owing to their high specific stiffness and strength. Although unidirectional (UD) prepreg systems provide superior mechanical performance, their high material and processing costs have motivated increasing interest in textile-based reinforcements and out-of-autoclave manufacturing techniques, such as vacuum-assisted resin infusion (VARI). In VARI processes, laminate thickness is not constrained by a rigid mold cavity and is therefore strongly governed by the reinforcement architecture and resin uptake behavior. In this study, the influence of the areal weight (AW) of unidirectional carbon fiber reinforcement on laminate thickness in vacuum-infused composites is systematically investigated. Non-crimp stitched UD carbon fabrics, with measured carbon areal weights ranging from 596.6 to 634.9 g/m², were manufactured by varying the tow density across the fabric width. The compaction behavior of dry fabrics was evaluated using 100-ply stacks under vacuum, while the thickness and fiber volume fraction of cured laminates were determined from 20-ply infused specimens. The results demonstrate a strong linear correlation between carbon AW and cured ply thickness (CPT) ($R^2 \approx 0.93$), indicating that laminate thickness increases predictably with increasing reinforcement mass per unit area. Specifically, an increase of 10 g/m² in carbon AW corresponds to an average increase of approximately 0.035 mm in CPT. Similarly, the dry stack thickness under vacuum exhibits a strong linear dependence on AW ($R^2 \approx 0.90$), whereas the fiber volume fraction (FVF) shows a slight decreasing trend with increasing AW. These findings provide quantitative design guidelines for thickness prediction and reinforcement selection in infusion-based manufacturing of unidirectional CFRP laminates, particularly for applications where geometric constraints are minimal or absent.

1. Introduction

The compaction mechanics of dry fiber reinforcements have long been described through multi-scale deformation mechanisms such as tow cross-section compression, pore collapse, and yarn bending, which together dictate nonlinear pressure–thickness behavior [1]. Subsequent studies on woven and non-crimp multiaxial reinforcements showed that nesting, initial packing state, and yarn geometry strongly influence compaction stiffness and achievable fiber volume fractions [2-4]. Other research demonstrated that tow-level deformation and interlayer alignment lead to architecture-dependent consolidation behaviors, reinforcing the role of reinforcement mass and packing in determining laminate thickness [5,6].

Permeability is closely coupled to compaction. Investigations on shear-deformed dry reinforcements revealed that tow rotation, fiber alignment, and compaction alter the permeability tensor and modify flow behavior during infusion [7,8]. VARI-based studies further demonstrated that laminate thickness evolves dynamically during infusion due to pressure gradients, lubrication effects, and partial elastic recovery of the fiber bed—changes that depend on the preform's initial compaction and packing density [9]. These findings indicate that AW, which governs tow geometry and pore structure, influences both dry-stack thickness and flow-induced thickness changes.

Additional insights from infusion on curved molds showed that preform deformation, local compaction, and race-tracking channels create permeability variations and thickness non-uniformities, driven by local fiber packing conditions [10]. Meanwhile, studies comparing bindered and unbindered carbon NCF laminates demonstrated that preforming cycles, binder activation, compaction level, and flow direction all affect final thickness, void content, and fiber volume fraction—yet these effects consistently stem from the initial dry-stack packing determined by reinforcement mass per unit area [11].

Recent research on multi-ply preforming mechanics further highlighted how inter-ply friction, evolving contact area, and nesting behavior under vacuum influence compaction and through-thickness stiffness [12]. Although these studies span woven, stitched, and multiaxial materials, the underlying conclusion still applies to UD systems: higher AW increases fiber packing density and enhances tow-tow interactions, thereby intensifying consolidation and thickness reduction under vacuum.

Despite extensive literature on compaction, permeability, nesting, and forming behavior across various fiber architectures, no systematic study has isolated the specific effect of reinforcement AW on laminate thickness for UD carbon fiber composites processed via liquid composite molding (LCM). Since UD reinforcements lack crimp and deform mainly through tow cross-section compression, their consolidation is more directly governed by AW than in multiaxial or woven fabrics.

This study addresses this gap by examining UD carbon fiber NCF reinforcements with varying areal weights and quantifying their influence on; (i) dry-stack compaction under vacuum, (ii) thickness evolution during resin infusion, and (iii) final cured laminate thickness and fiber volume fraction.

Through integrated compaction and infusion analyses, the work establishes a clear mechanistic relationship between AW and laminate thickness, enabling more reliable prediction and process optimization for UD composites manufactured via LCM.

2. Experimental study

2.1. Materials

The reinforcement used was a non-crimp stitched unidirectional carbon fiber fabric supplied by METYX Composites. The fabric featured carbon fibers aligned in the 0° direction with nominal areal weights ranging from 596.6 to 626.0 g/m² as given in Table 1, combined with 68 tex E-glass fibers (63.3 g/m²) in the 90° direction and polyester stitch yarn (19.8 g/m²) for structural integrity. The variation in the areal weight of the carbon fiber layer was achieved by adjusting the tow density across the fabric width. This was accomplished by distributing the carbon fiber tows at different spacings using combs with varying tooth densities during fabric formation. The carbon fiber used was 50K (3650 Tex) Zoltek Panex 35, a high-performance PAN-based fiber. The matrix system was an epoxy resin, Duratek DT1204, selected for its compatibility with vacuum-assisted resin infusion processes. The density of carbon fiber was taken as 1.8 g/cm³, and that of the epoxy resin as 1.2 g/cm³; these values were used in the calculation of the fiber volume fraction according to EN ISO 1172.

Although the areal weight of the fabrics was initially adjusted based on theoretical calculations, variations in yarn linear density may result in deviations from the target values. Therefore, areal weight measurements were conducted in accordance with ISO 3374. Three specimens were taken across the width of each fabric roll, from one edge to the other, in order to capture transverse variability. In addition, samples were collected from multiple fabric rolls, yielding a total of 15 measurements. The average of these measurements was used in all subsequent calculations.

Table 1. Areal weight range of the carbon fabrics used in the study

Sample code	Tow count	Theoretical areal weight of carbon layer, g/m²
R15.5	77	596.6
R16.0	79	605.0
R16.2	80	610.0
R16.5	81	616.6
R17.0	84	626.0

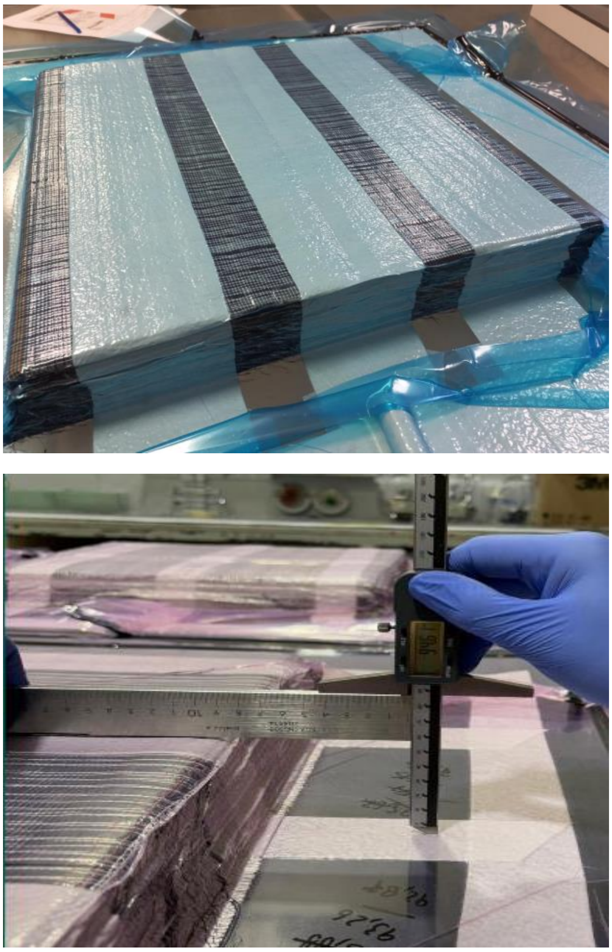

Fig. 1. Zones A, B, and C identified for thickness measurement under vacuum compaction

2.2. Dry fabric stacking and thickness measurement

Fabric rolls were cut into 50 cm × 50 cm plies using an electric rotary cutter to ensure dimensional accuracy. A laser cross-marker was employed to align fiber orientations precisely during stacking, ensuring that 0° carbon fibers and 90° glass fibers were consistently positioned across all layers.

To evaluate the compaction behavior of different fabrics prior to resin infusion, a dry lay-up of 100 plies was prepared for each areal weight configuration. The stacks were placed under vacuum at around −950 mbar without resin infusion, simulating preform consolidation conditions. Thickness measurements were performed using a calibrated digital gauge.

To account for possible thickness variation across the stack, measurements were taken in three zones (A, B, and C) along the width of the laminate, as shown in Fig. 1. In each zone, two measurements were recorded, resulting in six readings per stack. The mean and standard deviation were calculated for each fabric type.

2.3. Infusion and cured ply thickness measurement

For cured thickness evaluation, laminates were fabricated using 20 plies of unidirectional carbon fabric under vacuum-assisted resin infusion (See Fig. 2 & Fig. 3). The epoxy system was Duratek DT1204 with hardener DTS1154, infused at a resin temperature of 23 °C and viscosity of 270 ± 50 cP. Vacuum level was maintained at −950 mbar, and the total infusion time was varied between 40-45 minutes. During infusion, the room temperature and the relative humidity values were 23.5 °C and 35% respectively. After curing, the laminate was sectioned along its centerline, and thickness measurements were taken at eight different locations on the cut section using a calibrated micrometer. The cured ply thickness was calculated by dividing the measured laminate thickness by the total number of fabric plies used in the layup, which was 20.

The fiber weight fraction was determined in accordance with the EN ISO 1172 test standard, with measurements repeated three times to ensure accuracy and repeatability.

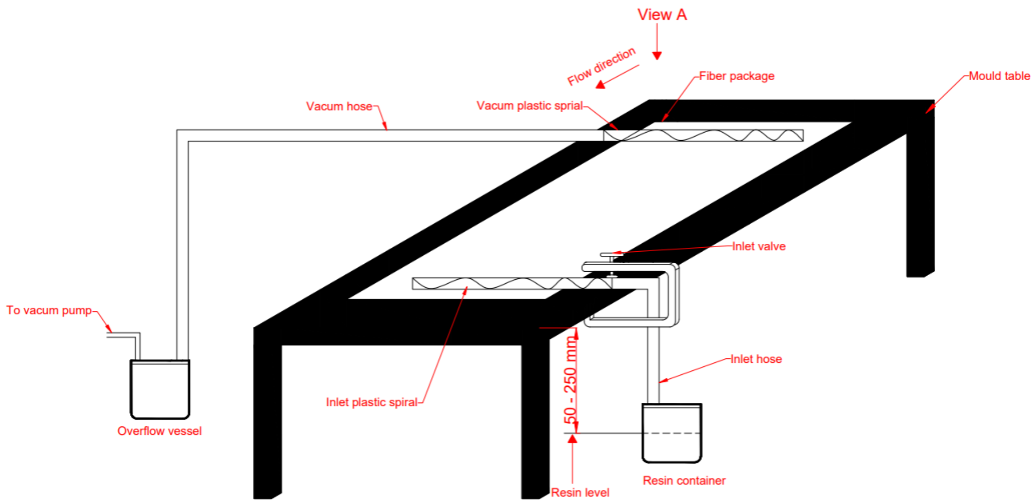

Fig. 2. Schematic presentation of vacuum-assisted resin infusion set up

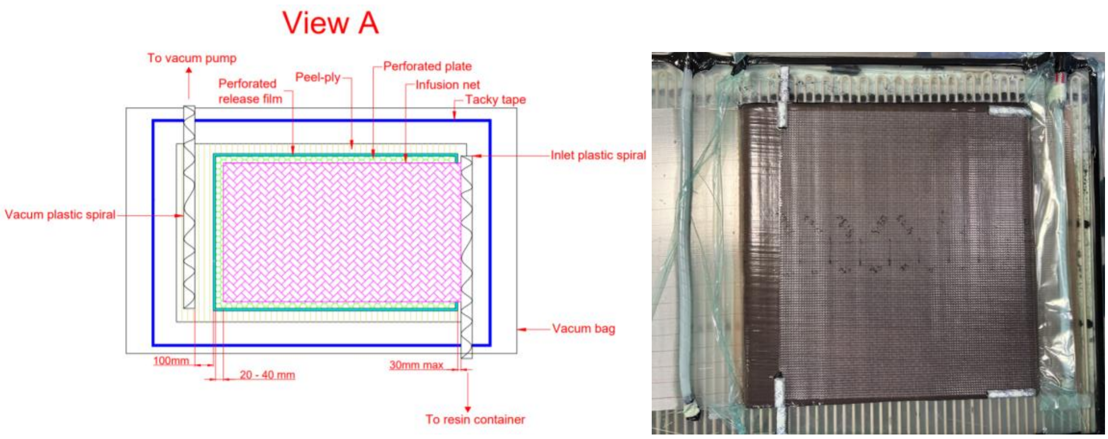

Fig. 3. Top view of vacuum-assisted resin infusion set up (left) and manufactured laminate (right)

3. Results

3.1. Effect of carbon areal weight on cured ply thickness

Fig. 4 illustrates the relationship between the measured carbon fiber areal weight and the cured ply thickness of the infusion laminates. A clear positive linear trend is observed, indicating that increasing areal weight leads to a systematic increase in cured ply thickness. Specifically, as the measured areal weight increases from 596.6 g/m² (R15.5) to 634.9 g/m² (R17.0), the cured ply thickness correspondingly increases from 0.652 mm to 0.787 mm.

Linear regression analysis confirms a strong correlation between areal weight and cured ply thickness, demonstrating that ply thickness can be reliably predicted as a function of reinforcement mass per unit area under constant infusion and curing conditions. The relatively low standard deviations of cured ply thickness (n = 3), ranging from 0.0052 mm to 0.0266 mm, indicate good repeatability of laminate consolidation during the vacuum infusion process. The slightly higher scatter observed for sample R16.2 is attributed to local variations in fiber packing density and resin distribution.

These results demonstrate that, in the absence of a rigid mold cavity, laminate thickness control in vacuum infusion processes is predominantly governed by reinforcement areal weight rather than tooling constraints.

3.2. Relationship between carbon areal weight and fiber volume fraction

Fig. 5 presents the variation of fiber volume fraction as a function of carbon areal weight. In contrast to ply thickness, fiber volume fraction shows a slight decreasing trend with increasing areal weight. While the areal weight increased across the sample set, the fiber volume fraction decreased from 54.72% (R15.5) to approximately 53.3% (R17.0).

This behavior suggests that although more fiber mass is introduced per unit area, the laminate thickness increases at a proportionally higher rate, leading to increased resin accommodation within the laminate. As a result, the relative fiber volume fraction decreases slightly. The calculated fiber volume fractions fall within a narrow range (53–55%), which is typical for high-quality vacuum-infused CFRP laminates.

The standard deviation of fiber volume fraction (n = 3) remains relatively low for most samples, indicating stable resin impregnation and consolidation. The higher deviation observed for R16.2 (±1.32%) may be associated with local non-uniformity in fiber bundle spacing or resin flow during infusion.

3.3. Influence of carbon areal weight on dry fabric stack thickness

The effect of carbon areal weight on the dry fabric stack thickness under vacuum is shown in Fig. 6. A strong positive linear relationship is observed between areal weight and the dry thickness of 100-ply fabric stacks. As the areal weight increased, the dry stack thickness increased from 64.01 mm (R15.5) to 74.67 mm (R17.0).

This trend reflects the increased fiber bundle density and tow count across the fabric width, resulting in thicker compressed stacks even under vacuum. The relatively low standard deviations of dry thickness measurements (n = 6), ranging between 0.245 mm and 0.935 mm, demonstrate consistent compaction behavior of the dry reinforcements.

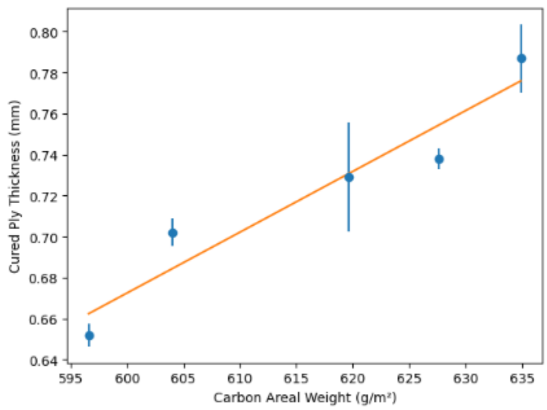

Fig. 4. Relationship between carbon fiber areal weight and cured ply thickness of infusion laminates

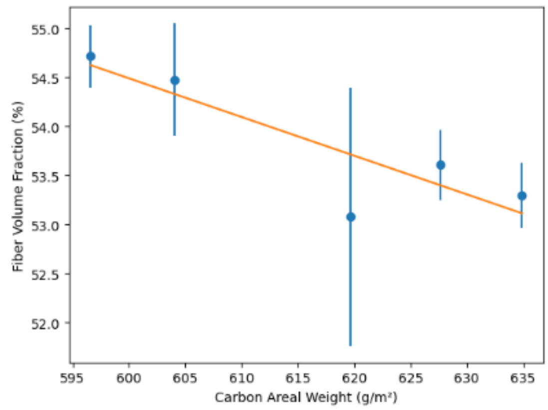

Fig. 5. Variation of fiber volume fraction as a function of carbon fiber areal weight

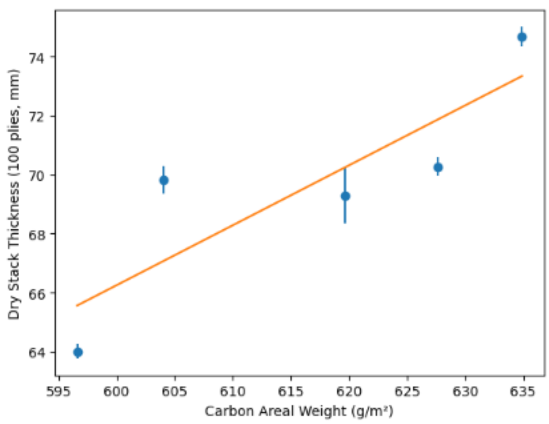

Fig. 6. Effect of carbon fiber areal weight on dry fabric stack thickness under vacuum

The comparison between dry stack thickness and cured laminate thickness indicates that fabrics with higher areal weight exhibit lower relative compaction efficiency during infusion, as thicker fiber bundles create more pronounced resin-rich regions. This observation further supports the decrease in fiber volume fraction observed at higher areal weights.

3.4. Overall discussion

A clear linear relationship was observed between the carbon fiber areal weight (AW) and the cured ply thickness (CPT). As AW increased from 596.6 to 634.9 g/m², the CPT increased proportionally from 0.652 mm to 0.787 mm. To quantify the strength of this linear relationship, the coefficient of determination (R^2) was calculated based on the standard least-squares regression as

$$R^2 = 1 - \frac{\sum(y_i - \hat{y}_i)^2}{\sum(y_i - \bar{y})^2} \quad (1)$$

where y_i represents the experimentally measured thickness values, $\hat{y}_i$ are the predicted thickness values obtained from the linear regression model, and $\bar{y}$ is the mean of the measured data. The numerator corresponds to the unexplained variance (residual sum of squares), while the denominator represents the total variance in the dataset.

Using Eq. (1), the resulting $R^2 \approx 0.93$ indicates that approximately 93% of the variance in cured ply thickness is explained solely by changes in areal weight. In practical terms, this means that AW serves as a highly reliable predictor of laminate thickness in vacuum-infused UD composites. The regression slope further quantifies this relationship: an increase of 10 g/m² in AW corresponds to an average CPT increase of ~0.035 mm, confirming a strong and predictable proportionality.

A similar correlation was found for the dry-stack thickness under vacuum. Increasing AW by 38 g/m² resulted in an increase of about 10.7 mm in the thickness of the 100-ply stack. The corresponding regression yielded $R^2 \approx 0.90$, demonstrating that 90% of the variability in dry compaction thickness is governed by fiber mass per unit area. This agreement between the dry-stack and cured-laminate R^2 values indicates that the consolidation behavior of the preform is largely preserved during infusion and curing, despite resin flow-induced relaxation effects.

In contrast, the relationship between AW and fiber volume fraction (FVF) showed a weaker linear trend, reflected by a lower $R^2 \approx 0.70$. This can be attributed to process-dependent variables such as local tow rearrangement, varying permeability, and resin distribution differences during infusion. As AW increases, laminate thickness also increases, but this expansion allows slightly more resin to be accommodated, leading to a modest decrease in FVF from ~54.7% to ~53.3%. The larger scatter in FVF data—consistent with the lower R^2—suggests that FVF is influenced not only by reinforcement AW but also by resin flow characteristics and local variations in compaction efficiency. To further elucidate the effect of compaction efficiency on fiber volume fraction (FVF), a compaction ratio was defined based on the relative difference between the dry ply thickness measured under vacuum and the cured ply thickness. Table 2 presents the compaction ratio and FVF for each AW condition. The dry ply thickness values presented in this table were obtained by dividing the dry stack thickness values measured using a 100-ply layup in Section 3.3 by the corresponding ply count of 100. The cured ply thickness values were calculated in Section 2.3 and are presented in Fig. 4.

The compaction ratio was calculated according to Eq. (2) by subtracting the cured ply thickness from the dry ply thickness, normalizing this difference by the dry ply thickness, and expressing the result as a percentage:

$$CR = \frac{t_{dry} - t_{cured}}{t_{dry}} \times 100 \quad (2)$$

The calculated compaction ratio was then correlated with the corresponding FVF values to assess the influence of compaction behavior on fiber volume fraction. Negative compaction ratio values indicate that the cured laminate thickness exceeds the dry preform thickness, implying partial opening of the fiber bed due to resin infiltration.

For the first two samples, corresponding to lower AW values, relatively lower magnitude compaction ratios are observed compared to the remaining three samples, accompanied by higher FVF values. This indicates reduced resin uptake for these laminates, which is consistent with their higher FVFs. Conversely, for the higher AW samples, compaction ratios exceeding −5% suggest increased resin uptake, as reflected by both the larger thickness increase and the lower FVF values. Although variations in AW do not result in a strictly linear trend in the compaction ratio, an increase in AW is associated with increased resin uptake during infusion. As the tow count and tow density across the fabric width increase, the higher fiber mass per unit area reduces the compressibility of the dry stack under vacuum. This reduced compressibility leads to thicker cured plies after infusion and curing, indicating that AW primarily influences laminate thickness through its effect on dry preform resistance to compaction and subsequent resin accommodation rather than through a monotonic change in compaction ratio.

Overall, integrating the R^2 calculations with the experimental trends confirms that areal weight is the dominant parameter governing both dry and cured laminate thickness, while its influence on FVF is secondary and mediated by resin flow and compaction interactions. These findings establish a predictive and quantitatively validated framework for thickness control in infusion-based manufacturing of UD carbon fiber composites.

Table 2. Areal weight, compaction ratio and fiber volume fraction evaluation

Sample code	Measured areal weight, g/m²	Cured ply thickness, mm	Dry ply thickness, mm	Compaction ratio (%)	Fiber volume fraction, %
R15.5	596.60	0.6401	0.6525	-1.93	54.72
R16.0	604.00	0.6983	0.7021	-0.54	54.48
R16.2	619.68	0.6930	0.7290	-5.19	53.08
R16.5	627.66	0.7027	0.7383	-5.06	53.61
R17.0	634.90	0.7467	0.7874	-5.44	53.30

4. Conclusion

In this study, the influence of carbon fiber areal weight on laminate thickness, dry fabric stack thickness, and fiber volume fraction was systematically investigated for infused unidirectional carbon fiber composites. Since the vacuum-assisted resin infusion (VARI) process does not impose a fixed mold cavity thickness, laminate thickness control was shown to be primarily governed by reinforcement architecture and resin-to-fiber ratio.

The results demonstrate a clear and nearly linear increase in both dry fabric stack thickness and cured ply thickness with increasing carbon fiber areal weight. As the tow count and tow density across the fabric width increased, higher fiber mass per unit area led to reduced compressibility of the dry stack under vacuum and consequently thicker cured plies after infusion and curing. This confirms that fabric architecture plays a dominant role in thickness development for infusion-based manufacturing routes.

Linear regression analysis of carbon areal weight versus cured ply thickness revealed a strong positive correlation. Based on the regression slope obtained from the experimental data, an increase of approximately 10 g/m² in carbon fiber areal weight corresponds to an increase of about 0.035 mm in cured ply thickness. Equivalently, a 100 g/m² increase in areal weight results in an average cured ply thickness increase of approximately 0.35 mm. This quantitative relationship provides a practical design rule for predicting laminate thickness in infusion processes where geometric constraints are absent.

In contrast, fiber volume fraction exhibited a weak negative trend with increasing carbon areal weight. Although higher areal weights increased ply thickness, the fiber volume fraction slightly decreased due to reduced compaction efficiency and increased resin retention within the laminate. Nevertheless, the variation in fiber volume fraction remained within a relatively narrow range, indicating stable process control.

Overall, the findings highlight that carbon fiber areal weight is a critical parameter for thickness prediction and process design in vacuum-assisted resin infusion of unidirectional composites. The derived linear relationship between areal weight and cured ply thickness can be directly utilized in laminate design, thickness tolerance control, and numerical modeling of infusion-based composite structures.

Declarations

Conflict of interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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This research received no external funding.

Author contributions

All authors contributed equally to this study. All authors have read and approved the final manuscript and accept equal responsibility for its content.

Data availability statement

The data presented in this study are available on request from the corresponding author.

Use of generative AI and AI-assisted technologies

The author(s) confirm the author(s) did not use any AI tools in the preparation of this work/research/study.

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