

MICROSCALE AIR PERMEABILITY CHARACTERIZATION OF LAFP COMPOSITES USING MICRO-CT IMAGING: COMPARISON WITH PULSE-DECAY MEASUREMENTS

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Abstract

Vacuum bag only (VBO) processing has gained increasing interest as an out-of-autoclave (OoA) route for composite consolidation, offering an alternative to conventional autoclave-based manufacturing. For this process to be effective, the laminate must provide adequate air-flow pathways to allow trapped air to be removed during consolidation. In laser-assisted fiber placement (LAFP), the development of these pathways is governed by both the selected processing conditions and the stacking sequence of the laminate. Although the pulse-decay method is widely applied for measuring the permeability of low-permeability porous materials, its use for composite laminates can be time-consuming and requires relatively large, well-sealed specimens. Moreover, it does not directly reveal the internal pore-network structure. X-ray micro-computed tomography (Micro-CT) provides a non-destructive alternative that enables three-dimensional analysis of void morphology, pore connectivity, and fiber arrangement. In this work, the air permeability of LAFP-fabricated thermoplastic composite laminates produced with different lay-up speeds and stacking sequences was investigated using both pulse-decay and Micro-CT-based approaches. The two techniques showed comparable permeability trends across the examined configurations. In addition, Micro-CT provided detailed information on connected porosity and void morphology, with lower variability in the calculated permeability values. The results suggest that Micro-CT can be used as an effective tool for permeability evaluation and for supporting the optimization of LAFP processing toward OoA composite manufacturing.

Keywords: *laser-assisted fiber placement; air permeability; micro-CT; pulse-decay method; out-of-autoclave processing*

1 Introduction

Automated fiber placement (AFP) is widely used for manufacturing high-performance composite structures with high accuracy and repeatability [1]. Thermoplastic composites, such as CF/PEKK and CF/PEEK, are attractive for AFP because of their mechanical performance, impact resistance, recyclability, and unlimited shelf life [2]. However, the high melt viscosity of thermoplastic matrices makes in-situ consolidation difficult, and insufficient interlaminar contact can lead to void formation during lay-up [3].

In laser-assisted fiber placement (LAFP), void formation and interlaminar bonding are affected by processing parameters and laminate architecture, particularly lay-up speed and ply orientation [4,5]. These interlaminar features can also influence damage initiation and fracture behavior in composite laminates [6]. Voids may remain isolated or form connected micro-channels, which directly influence air permeability [7]. This is important for out-of-autoclave (OoA) processing, especially vacuum bag only (VBO) consolidation, where connected air pathways are required for air evacuation during the vacuum cycle [8].

Air permeability is commonly characterized using the pulse-decay method, but this method requires long testing times and carefully sealed specimens [9]. In contrast, X-ray micro-computed tomography (Micro-CT) provides non-destructive three-dimensional information on void morphology and connected porosity [10]. In this study, the air permeability of LAFP-manufactured CF/PEKK laminates was investigated for two stacking sequences, [0°/0°/0°] and [0°/90°/0°], fabricated at lay-up speeds of 100 and 400 mm/s. The objective was to evaluate the effects of lay-up speed and fiber-orientation mismatch on void connectivity and permeability, and to compare pulse-decay and Micro-CT-based permeability assessment methods.

2 Materials and experimental methods

Four CF/PEKK thermoplastic composite laminates were manufactured using laser-assisted fiber placement (LAFP). Two stacking sequences, namely [0°/0°/0°] and [0°/90°/0°], were investigated at two lay-up speeds of 100 and 400 mm/s. The consolidation force was kept constant at 500 N for all laminates. The corresponding processing parameters are summarized in Table 1. The LAFP system was equipped with a fiber placement head capable of depositing thermoplastic tapes with a nominal tape width of 6.35 mm. A diode laser was used as the heating source, and a conformable compaction roller was employed to apply pressure during deposition. The tool temperature was maintained at 155 °C to support interlaminar bonding during lay-up. The laser power was adjusted according to the lay-up speed in order to maintain a suitable nip-point temperature during processing.

The laminates were initially manufactured with dimensions of 1100 mm × 152.4 mm. To remove the regions affected by transient start and end effects, each laminate was trimmed to a length of 900 mm. The plates were then divided into three strips with final dimensions of 900 mm × 50.8 mm. Trimming and sample preparation were performed using a robotic waterjet cutting system. For Micro-CT analysis, square coupons of 10 mm × 10 mm were extracted from the stabilized middle region of each laminate.

Table 1. LAFP processing parameters used for laminate fabrication.

Laminate stacking sequence	Lay-up speed [mm/s]	Consolidation force [N]	Corresponding laser power [W]
[0°/0°/0°]	100	500	1386
[0°/90°/0°]	100	500	1386
[0°/0°/0°]	400	500	3427
[0°/90°/0°]	400	500	3427

Air permeability was evaluated for each laminate configuration using both the pulse-decay method and Micro-CT. In the pulse-decay approach, the temporal pressure decay across the laminate was recorded and processed in MATLAB to calculate gas permeability normalized by

porosity. In the Micro-CT approach, high-resolution three-dimensional reconstructions of the internal void structure were analyzed to quantify porosity, estimate permeability from the identified pore network, and calculate the normalized permeability, for comparison with the pulse-decay results.

2.1 Air permeability assessment with pulse-decay method

Air permeability was measured using the pulse-decay method, in which vacuum was applied to one side of the specimen while the pressure variation on the opposite side was continuously recorded. The pressure-decay rate is governed by Darcy-type gas flow through the internal pore network and is therefore related to the permeability of the laminate. A schematic illustration of the method and the experimental setup is shown in Figure 1.

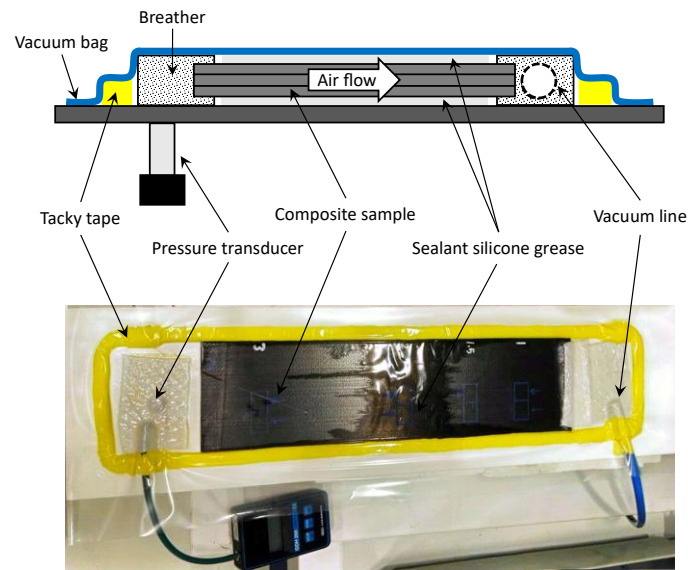


Figure 1. Schematic (top) and experimental setup (bottom) for pulse-decay gas flow characterization.

To ensure that air flow occurred mainly through the internal pore network, silicone grease was applied between the specimen surfaces and the vacuum bag on both sides. Tacky tape was also used along the specimen edges and around the pressure sensor connection to improve sealing and prevent leakage. The vacuum side was connected to a laboratory vacuum line with an absolute pressure of 0.07 bar, while the pressure decay was measured on the opposite side using a low-pressure transmitter. Pressure data collected using LabVIEW at a sampling frequency of 110 Hz for 24 h under ambient laboratory conditions at 25 °C.

The measured pressure-decay data were analyzed using the pulse-decay formulation proposed by Cender et al. [9]. In this method, the characteristic time of the pressure-decay response is related to the permeability of the porous medium as follows:

$$t_c = \frac{\phi \mu L^2}{K_l (P_i - P_f)} \quad (1)$$

where ϕ is the effective porosity, μ is the viscosity of air, L is the specimen length, K_l is the intrinsic liquid permeability, and P_i and P_f are the initial atmospheric and final vacuum pressures, respectively. The experimental pressure-decay curves were fitted to the numerical

solution in MATLAB by minimizing the residual error between the measured and calculated pressure responses. The obtained characteristic time and Klinkenberg parameter were then used to determine gas permeability. The gas permeability was related to intrinsic permeability using the Klinkenberg correction:

$$K_g = K_l \left(1 + \frac{b}{P_f}\right) \quad (2)$$

where K_g is the gas permeability, b is the Klinkenberg parameter. Since the pulse-decay formulation provides permeability normalized by effective porosity, the final permeability value was reported as K_g/ϕ , which was later compared with the Micro-CT-based normalized permeability values.

2.2 Air permeability measurement by Micro-CT

Micro-CT was used as a non-destructive technique to characterize the internal void structure of the LAFP-manufactured laminates. This method enables three-dimensional visualization of pores and provides quantitative information on void morphology, distribution, and connectivity [10–12].

Micro-CT scans were performed using a Baker Hughes Phoenix V|tome|x M 300/180 system. A viewing area of 6 mm × 6 mm and a voxel size of 8 μm were selected to provide sufficient resolution for porosity analysis. The scans were conducted at 70 kV and 120 μA without physical filters. For each specimen, approximately 1600 projections were acquired and reconstructed using Datos|x software. The reconstructed volumes were then analyzed in VGSTUDIO MAX to visualize the void structure and extract cross-sectional images. The complete scanning and reconstruction process required approximately 2 h per sample.

After 3D reconstruction, six equally spaced cross-sections were extracted along the x-direction, as shown in Figure 2. This direction corresponds to the permeability measurement direction in the pulse-decay test and the 0° fiber direction of the first and third plies in all stacking sequences. The extracted sections were exported as 2D images and analyzed in ImageJ using pixel area analysis to quantify porosity. Among the six sections, the cross-section with the lowest porosity, indicated as A–B in Figure 2(b), was selected for permeability estimation. This section represents the minimum preserved flow area along the connected void pathway and therefore provides a conservative estimate of air transport through the laminate.

For the Micro-CT-based permeability calculation, the connected void area in the selected cross-section was approximated as an equivalent circular flow channel. The equivalent pore radius, R_{eq} , was calculated from the measured connected void area, and the air permeability, K_g , was estimated using Equation (3):

$$K_g = \frac{R_{eq}^2}{8} \quad (3)$$

This expression is based on the analogy between Darcy's law for porous media flow and the Hagen–Poiseuille equation for laminar flow through a cylindrical channel [13]. Although this approach simplifies the actual void network geometry, it provides a practical first-order estimate of Micro-CT-based permeability and enables comparison with the pulse-decay results.

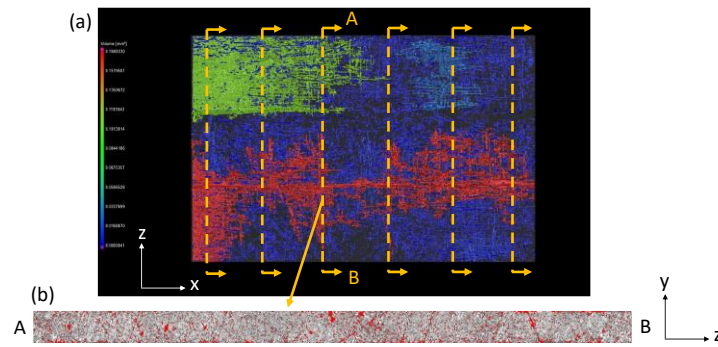


Figure 2. (a) Six equally spaced yz cross-sections extracted along the x-direction, and (b) the A–B cross-section used to illustrate the ImageJ-based analysis procedure.

3 Results and discussion

Figure 3 presents representative pressure decay curves obtained from the pulse-decay measurements for the $[0^\circ/0^\circ/0^\circ]$ and $[0^\circ/90^\circ/0^\circ]$ laminates fabricated at lay-up speeds of 100 and 400 mm/s. The $[0^\circ/0^\circ/0^\circ]$ laminates showed almost no pressure decay during the test, indicating negligible air permeability. This behavior suggests that the unidirectional configuration contains very limited interconnected porosity, mainly due to fiber nesting and resin flow at the interlaminar region. In contrast, the $[0^\circ/90^\circ/0^\circ]$ laminates exhibited clear pressure decay, confirming the presence of connected void pathways. The pressure drop was more pronounced at 400 mm/s, indicating that higher lay-up speed promotes the formation of more effective air-flow channels.

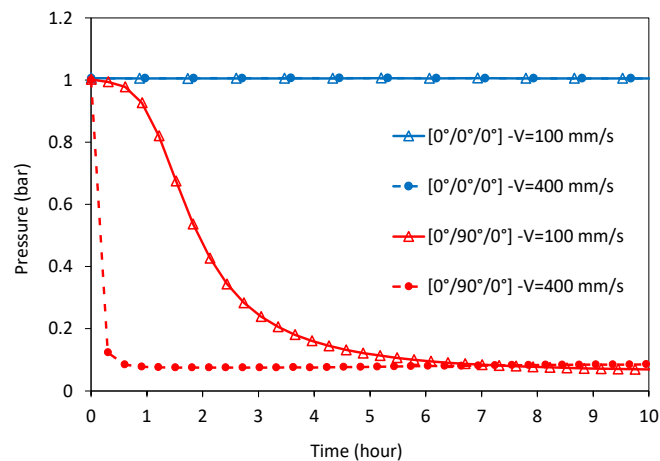


Figure 3. Pressure decay curves obtained from the pulse-decay method for $[0^\circ/0^\circ/0^\circ]$ and $[0^\circ/90^\circ/0^\circ]$ laminates fabricated at lay-up speeds of 100 and 400 mm/s.

Since the $[0^\circ/0^\circ/0^\circ]$ laminates did not show measurable pressure decay, they were excluded from the quantitative pulse-decay permeability calculation. For the $[0^\circ/90^\circ/0^\circ]$ laminates, the pressure decay curves were fitted to the numerical model described in Section 2.1, and the average permeability values normalized by porosity, K_g/ϕ , obtained from three tests at each lay-up speed, are summarized in Table 2. Increasing the lay-up speed from 100 to 400 mm/s increased K_g/ϕ from 3.54×10^{-8} to 6.70×10^{-8} mm², corresponding to an increase of approximately 89%. At the same time, the Klinkenberg parameter decreased from 24.17 to 12.26 kPa, suggesting an increase in the effective pore size. These results indicate that the higher

lay-up speed reduces the available time for heat transfer, compaction, and matrix flow, thereby preserving larger and more connected interlaminar void pathways.

Table 2. Average porosity-normalized permeability results obtained from pulse-decay measurements for LAFP-fabricated [0°/90°/0°] laminates.

Laminate stacking sequence	Lay-up speed (mm/s)	b (KPa)	K_g/ϕ (mm ²)
[0°/90°/0°]	100	24.17	3.54×10^{-8}
[0°/90°/0°]	400	12.26	6.70×10^{-8}

Micro-CT analysis was used to examine the internal void structure and connected porosity of the laminates. As shown in Figure 4, the color scale represents the relative void volume: blue regions correspond to the dense matrix, green indicates medium-sized voids, and red represents larger voids or regions with higher porosity. The [0°/0°/0°] laminates showed mainly blue regions with limited green or red areas, indicating low void content and the absence of continuous connected pathways. This supports the negligible permeability observed in the pulse-decay tests. In contrast, the [0°/90°/0°] laminates showed more green and red regions, particularly at 400 mm/s, confirming that the cross-ply interface and higher lay-up speed promote connected void formation and improve air-flow pathways.

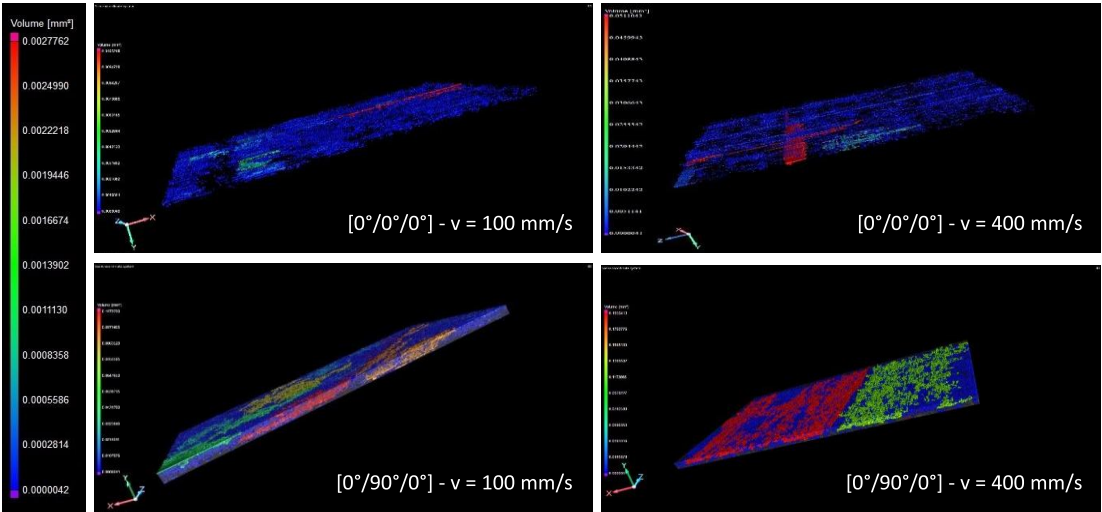


Figure 4. Micro-CT reconstruction porosity visualization of [0°/0°/0°] and [0°/90°/0°] laminates fabricated at lay-up speeds of 100 and 400 mm/s.

The main comparison between the two methods was performed using the average normalized gas permeability, K_g/ϕ , as shown in Figure 5. Both methods showed the same trend: the normalized permeability of the [0°/90°/0°] laminate increased with lay-up speed. The percentage difference between the two methods was 7.12% at 100 mm/s and 11.45% at 400 mm/s, indicating good agreement. In addition, the standard deviation values obtained from Micro-CT were lower than those from the pulse-decay method, suggesting better repeatability and less scatter. This can be attributed to the non-destructive analysis of small representative coupons and the reduced influence of sealing-related errors. Overall, these results show that Micro-CT can provide a reliable estimate of normalized permeability while also giving direct information about void morphology and porosity, which cannot be obtained from the pulse-decay method alone.

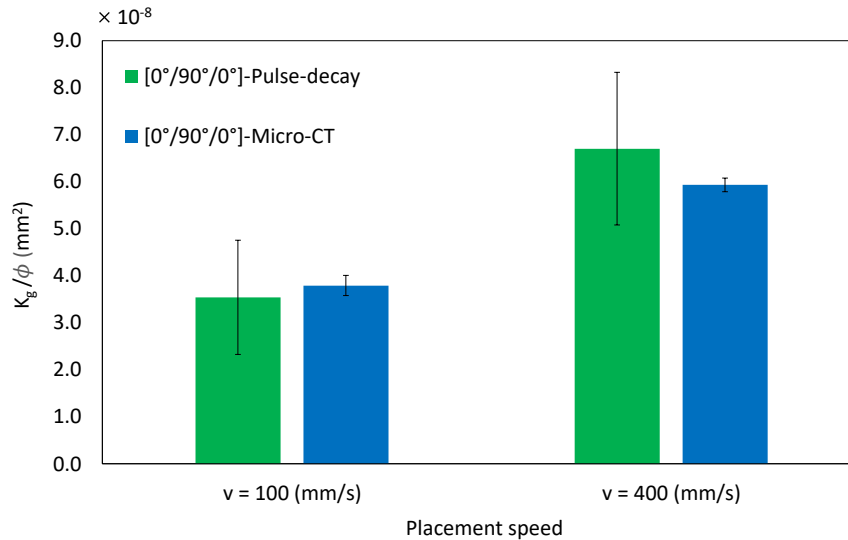


Figure 5. Comparison of average normalized gas permeability obtained from the pulse-decay method and Micro-CT for $[0^\circ/90^\circ/0^\circ]$ laminates fabricated at 100 and 400 mm/s.

4 Conclusion

This study compared the air permeability of LAFP-manufactured CF/PEKK laminates with $[0^\circ/0^\circ/0^\circ]$ and $[0^\circ/90^\circ/0^\circ]$ stacking sequences fabricated at lay-up speeds of 100 and 400 mm/s. The pulse-decay results showed negligible air permeability for the $[0^\circ/0^\circ/0^\circ]$ laminates, indicating limited interconnected air-flow pathways. In contrast, the $[0^\circ/90^\circ/0^\circ]$ laminates exhibited measurable permeability, which increased at the higher lay-up speed.

Micro-CT observations confirmed that the $[0^\circ/90^\circ/0^\circ]$ configuration promoted higher porosity and more continuous void pathways, especially at 400 mm/s. The comparison of average normalized gas permeability, K_g/ϕ , showed good agreement between the pulse-decay and Micro-CT methods, with percentage differences of 7.12% and 11.45% at 100 and 400 mm/s, respectively. In addition, Micro-CT showed lower standard deviation, indicating better repeatability and reduced scatter.

Overall, the results demonstrate that Micro-CT can be used as a reliable and efficient method for estimating normalized permeability while also providing useful information on void morphology and porosity. The findings also show that lay-up speed and fiber-orientation mismatch strongly affect air evacuation capability, which is important for optimizing LAFP composites for vacuum bag only processing.

Acknowledgements

The authors acknowledge the support of Sabanci University Integrated Manufacturing Technologies Research and Application Center (SU-IMC) for providing the manufacturing and characterization facilities used in this study.

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