

Assessment of Localized Mid-Plane and Through-Thickness Porosity in CFRP Laminates Using Ultrasonic Volume Imaging

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Abstract. Conventional porosity characterization in carbon fiber reinforced polymer (CFRP) laminates commonly relies on average through-thickness measurements to describe internal porosity content. However, global averaging may not adequately represent localized porosity concentration within mechanically and structurally important regions of the laminate. This study investigates the relationship between localized mid-plane porosity and average through-thickness porosity using three-dimensional ultrasonic nondestructive evaluation (3D-NDE). CFRP laminates were characterized using ultrasonic scanning and image-based porosity quantification. Average through-thickness porosity was determined using all reconstructed ultrasonic layers, whereas localized mid-plane porosity was quantified within a predefined region of interest centered around the laminate mid-plane. For specimens fabricated under a medium vacuum level (−330 mmHg), localized mid-plane porosity reached 8.6%, compared with an overall average porosity of 6.4%, corresponding to an approximately 34% increase relative to the laminate average. This behavior was observed for the medium-vacuum specimens investigated in this study. The findings demonstrate that average through-thickness porosity measurements do not always reflect localized mid-plane porosity distribution and indicate that localized mid-plane porosity characterization can provide complementary information for evaluating laminate quality. This study establishes a methodological basis for future investigations relating localized mid-plane porosity to mechanical performance and damage evolution.

Keywords: Carbon Fiber Reinforced Polymer; Mid-Plane Porosity; Through-Thickness Porosity; Ultrasonic Nondestructive Evaluation; Laminate Quality.

1. Introduction

Porosity is one of the most influential manufacturing defects affecting the quality and reliability of CFRP composites as it alters local microstructure and contributes to variations in structural behavior. Consequently, accurate characterization of porosity distribution has become an important aspect of composite evaluation and process optimization. Previous studies have extensively investigated overall porosity content, porosity distribution, and the relationship between porosity, manufacturing conditions, and mechanical performance using a variety of mechanical testing, destructive characterization, and nondestructive evaluation approaches [1–12].

Abdelal and Donaldson reported increased porosity concentration near laminate mid-plane regions, indicating that porosity distribution through the laminate thickness is spatially nonuniform and that average through-thickness porosity does not always fully represent localized mid-plane porosity behavior within composite laminates [7]. In addition, localized microstructural features such as resin-rich regions and porosity have been recognized as important contributors to composite behavior and failure initiation, highlighting the importance of localized characterization approaches for evaluating internal laminate quality [13]. Several studies have further shown that porosity can degrade specific mechanical responses in

composite laminates, including interlaminar shear strength, tensile performance, fatigue response, and delamination resistance [8–12]. These findings highlight the importance of determining whether localized porosity descriptors, particularly at mechanically critical regions such as the laminate mid-plane, provide additional insight beyond conventional average porosity measurements.

Advances in ultrasonic characterization techniques have enabled improved assessment of internal porosity distributions and provided valuable insight into porosity variation across laminate thickness [14]. Despite these advances, most previous studies report porosity using average through-thickness values as representative descriptors of laminate quality [14]. However, the extent to which these global measurements adequately represent localized mid-plane porosity concentration within the laminate has received comparatively limited attention. The ability of averaging procedures to conceal localized mid-plane porosity accumulation and spatial heterogeneity highlights the need for additional characterization approaches capable of resolving localized porosity behavior and providing further insight into internal laminate quality.

Therefore, this study evaluates whether conventional average through-thickness porosity measurements adequately represent localized porosity concentration at the laminate mid-plane and examines the potential of localized mid-plane porosity as a complementary descriptor for characterizing internal porosity distribution. To achieve this objective, average through-thickness porosity is compared with localized mid-plane porosity in CFRP laminates using 3D-NDE.

2. Experimental Procedure

The CFRP composite specimens analyzed in this study were selected from a specimen set exhibiting different internal porosity contents. The specimens were fabricated at the University of Dayton, Dayton, Ohio, USA, by hand lay-up followed by vacuum bagging, in accordance with the ASTM standards and procedures reported previously by Hakim et al. [14]. The present study focuses on specimens fabricated under the medium-vacuum condition (–330 mmHg), from which eight specimens were analyzed.

The medium-vacuum condition (–330 mmHg) was selected because it represents an intermediate processing condition within the previously characterized specimen set, rather than an extreme low- or high-vacuum condition. Abdelal et al. [7] showed that vacuum level influences porosity content and that porosity distribution in composite laminates is spatially nonuniform, with many specimens exhibiting higher void area fractions near the laminate midsection. Their results also demonstrated variability in porosity distribution among specimens and locations within the same laminate, indicating that local porosity values can overlap across different vacuum conditions. Therefore, the medium-vacuum specimens provided a suitable representative case for evaluating whether localized mid-plane porosity differs from average through-thickness porosity.

As shown in Figure 1, the fabrication process included resin application and distribution, placement of a thin Teflon insert at the laminate mid-plane, vacuum bagging under –330 mmHg for 24 h, curing, panel cutting, and final specimen preparation. The Teflon insert was intentionally placed at the laminate mid-plane as part of the original specimen design for subsequent interlaminar fracture studies and was not introduced specifically to generate porosity

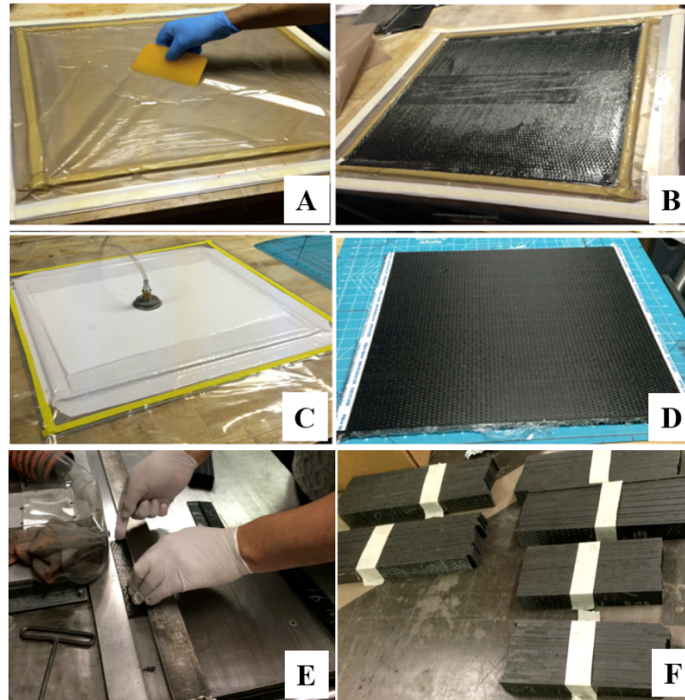


Figure 1. CFRP specimen fabrication process: (A) resin distribution, (B) placement of the Teflon insert at the panel mid-plane, (C) vacuum bagging with breather layer and vacuum-pump connection under -330 mmHg for 24 h, (D) cured panel before cutting, (E) specimen cutting, and (F) final prepared specimens.

Ultrasonic characterization was performed using a Sonoscan Gen5 ultrasonic microscopy system equipped with an Olympus Panametrics NDT V3193 transducer at Dresden University of Technology, Dresden, Germany. Measurements were conducted in pulse-echo immersion mode at a center frequency of 50 MHz using deionized water as the coupling medium. The specimen surface was scanned in two orthogonal directions, and the reflected ultrasonic signals were reconstructed to generate through-thickness ultrasonic images.

Although Hakim et al. [14] previously demonstrated the capability of ultrasonic microscopy to characterize porosity through the laminate thickness, the present study extends that work by evaluating whether average through-thickness porosity adequately represents localized porosity concentration at the laminate mid-plane. Porosity content was quantified from reconstructed ultrasonic images using the image processing and thresholding methodology reported previously by Hakim et al. [14]. Image processing and porosity quantification were performed using ImageJ software. Average through-thickness porosity was calculated using all reconstructed ultrasonic layers across the laminate thickness, whereas localized mid-plane porosity was determined separately from a predefined region of interest centered around the laminate mid-plane. A comparison between localized and global porosity descriptors was performed to evaluate whether average porosity measurements adequately represent localized porosity concentration.

Figure 2 schematically illustrates the localized mid-plane region of interest used for porosity evaluation in the CFRP laminate and conceptually represents a typical through-thickness porosity distribution, including localized porosity accumulation near the laminate mid-plane. The schematic is consistent with observations reported by Abdelal et al. [7], who found higher porosity area fractions near the laminate midsection than in adjacent layers.

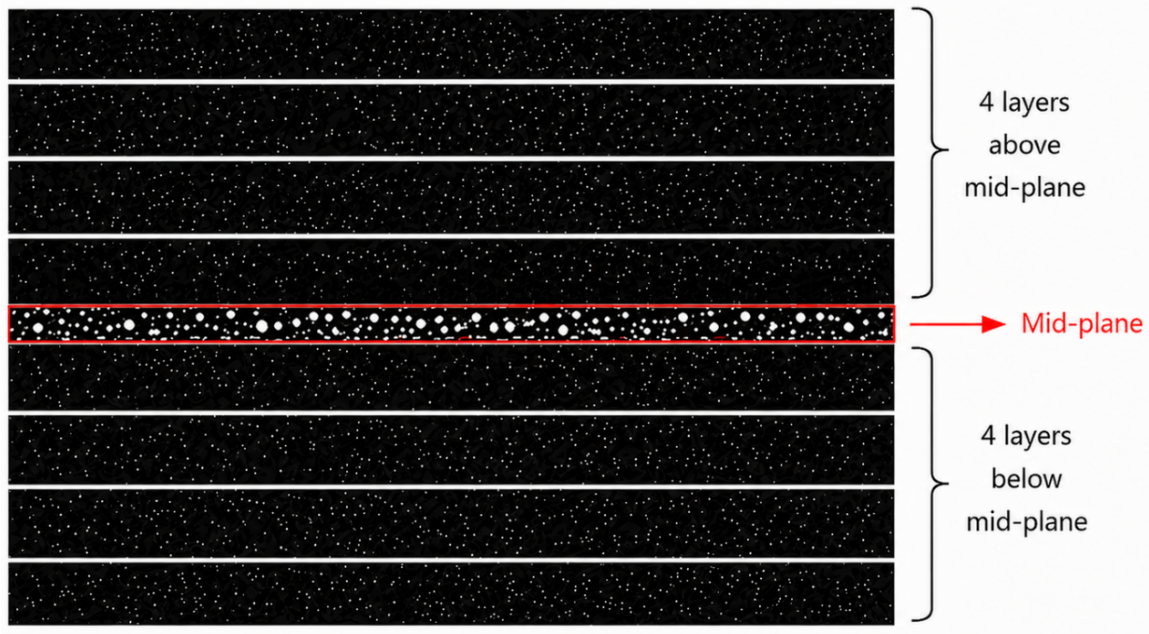


Figure 2. Front-view schematic illustration of the localized mid-plane region of interest used for porosity evaluation in the CFRP laminate.

The relative difference between localized mid-plane porosity and average through-thickness porosity was calculated as:

$$\text{Relative Difference (\%)} = \frac{P_{\text{mid}} - P_{\text{overall}}}{P_{\text{overall}}} \times 100 \quad (1)$$

Where P_{mid} is the localized mid-plane porosity and P_{overall} is the average through-thickness porosity.

3. Results

Table 1 summarizes the comparison between average through-thickness porosity and localized mid-plane porosity for the medium-vacuum specimens.

Table 1. Comparison between average through-thickness porosity and localized mid-plane porosity for CFRP specimens fabricated under medium-vacuum conditions (−330 mmHg), including the absolute difference and relative increase.

Parameter	Value
Vacuum level	−330 mmHg
Average through-thickness porosity (%)	6.4
Localized mid-plane porosity (%)	8.6
Absolute difference (percentage points)	2.2
Relative increase (%)	34.4

The average through-thickness porosity was 6.4%, whereas the localized mid-plane porosity reached 8.6%.

The relative increase in localized mid-plane porosity was calculated using Eq. (1) as:

$$\frac{8.6 - 6.4}{6.4} \times 100 = 34.4\%$$

Thus, localized porosity at the laminate mid-plane exceeded the overall laminate average by 2.2 percentage points, corresponding to a relative increase of 34.4%. These results indicate that localized mid-plane porosity and average through-thickness porosity did not provide equivalent descriptions of internal porosity distribution for the medium-vacuum specimens investigated in this study.

4. Discussion

Comparison between localized mid-plane porosity and overall average porosity showed that the two descriptors did not produce equivalent values for the medium-vacuum specimens. The localized mid-plane porosity reached 8.6%, whereas the overall average porosity was 6.4%, corresponding to an approximately 34% increase in localized mid-plane porosity relative to the laminate average. One possible explanation for this observation is the presence of the Teflon insert intentionally placed at the laminate mid-plane as part of the original specimen design for subsequent interlaminar fracture studies. Although the insert was not introduced specifically to generate porosity, its presence may alter local resin flow and consolidation behavior during fabrication. Local variations in resin distribution and disturbance of through-thickness pressure transmission around the insert region may influence void redistribution and retention, resulting in increased localized porosity near the laminate center.

Interpretation of localized mid-plane porosity measurements should also consider the influence of ultrasonic detectability with increasing laminate depth. The present study builds on the previously reported through-thickness ultrasonic characterization of the same CFRP specimen set, in which nonuniform porosity distribution and depth-dependent ultrasonic detectability were observed across the laminate thickness [14]. In that earlier work, the ability to detect internal porosity decreased with increasing laminate depth because of ultrasonic signal attenuation caused by backscattering and back reflection at fiber–matrix interfaces [9]. Consequently, some reconstructed ultrasonic images corresponding to the laminate mid-plane exhibited lower apparent porosity values due to reduced porosity detectability rather than actual reductions in porosity content.

Interpretation of localized mid-plane porosity measurements was also informed by previous characterization of the same specimen set using multiple complementary nondestructive, destructive, and mechanical evaluation approaches conducted in earlier studies [1–12, 14]. These investigations were performed on the same specimen population to enable direct comparison and correlation among different characterization techniques and mechanical responses. The availability of complementary characterization data provided additional context for interpreting localized porosity measurements and assessing their significance within the broader defect characterization framework. Therefore, interpretation emphasized reconstructed images exhibiting sufficient defect contrast and signal quality for reliable porosity quantification. Collectively, these findings indicate that localized porosity measurements should be interpreted in the context of both actual porosity distribution and depth-dependent ultrasonic detectability.

Although mechanical performance was not evaluated in the present study, this observation is important because the laminate mid-plane is commonly regarded as a mechanically significant region in composite laminates. Under interlaminar loading conditions, maximum interlaminar shear stresses are commonly developed near the laminate center. Therefore, localized mid-plane porosity is not fully represented by overall average porosity values and may influence mechanically critical regions differently than suggested by global porosity descriptors.

The observed trend is generally consistent with previous reports indicating that porosity in composite laminates is often spatially nonuniform and that average through-thickness porosity can mask localized

porosity concentration within internal laminate regions. In particular, Abdelal *et al.* [7] reported higher void area fractions near the laminate mid-plane than in adjacent layers for composites manufactured under several vacuum conditions. Their X-ray CT characterization further demonstrated that porosity concentration was generally greater near the laminate midsection than near the outer laminate regions. These observations support the present finding that localized mid-plane porosity exceeded the overall laminate average and therefore provided information not captured by conventional average through-thickness porosity measurements. Although this behavior was identified only for the medium-vacuum specimens in the present study, the observed 34.4% increase in localized mid-plane porosity should not be interpreted as a universal porosity distribution profile applicable to all processing conditions. Additional investigation is required to determine whether similar localized porosity behavior occurs under atmospheric-pressure or high-vacuum fabrication conditions. Nevertheless, the results demonstrate that localized mid-plane porosity descriptors provide additional information beyond conventional average through-thickness porosity measurements when evaluating internal laminate quality.

5. Conclusion

This study compared localized mid-plane porosity with average through-thickness porosity in CFRP laminates using 3D-NDE characterization. The main findings are summarized as follows:

1. Localized mid-plane porosity and average through-thickness porosity did not provide equivalent descriptions of internal porosity distribution for the medium-vacuum specimens investigated in this study.
2. For medium-vacuum specimens, localized mid-plane porosity reached 8.6%, whereas average through-thickness porosity was 6.4%, corresponding to an approximately 34% increase relative to the overall laminate average. This behavior was observed for the medium-vacuum specimens investigated and cannot yet be generalized to all fabrication conditions.
3. Ultrasonic attenuation effects should be considered when interpreting localized mid-plane porosity measurements because signal attenuation can reduce porosity detectability near the laminate mid-plane.
4. Localized mid-plane porosity characterization can provide complementary information beyond conventional average through-thickness porosity measurements when evaluating internal laminate quality.

Future studies should investigate the relationship between localized mid-plane porosity and mechanical behavior using short-beam shear (SBS) testing and interlaminar fracture toughness testing and determine whether localized porosity descriptors provide stronger correlations with structural performance than conventional average porosity measurements.

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Conflict of Interest

This statement is to certify that all authors have seen and approved the manuscript being submitted and to declare any competing interest.

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