Application of a Methodology for Void Structure Control in Continuous Fiber Additive Manufacturing for Space Structures

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KEYWORDS

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ABSTRACT

Continuous fiber-reinforced additive manufacturing (CF-AM) offers considerable potential for lightweight space structures by enabling high material efficiency, geometric flexibility, and functional integration. However, manufacturing-induced voids remain a critical challenge, as they directly influence structural performance and complicate process qualification. This paper presents the application of a methodology for the systematic characterization and prediction of void structures in continuous fiber-reinforced thermoplastic filaments. The methodology combines void subtype classification, image-based characterization, statistical regression, and physics-based analytical modelling to establish transferable process–structure relationships. Experimental investigations were conducted under controlled variations of key impregnation parameters to generate characteristic void morphologies. Regression analysis, together with physically based descriptors such as the modified capillary number and normalized impregnation depth, was used to identify the governing mechanisms of void formation and validate the predictive capability of the proposed framework. The results demonstrate that the methodology provides a defect-oriented assessment beyond conventional void content analysis, enabling a deeper understanding of process-dependent defect evolution. By linking manufacturing conditions to void subtype formation, the proposed approach supports qualification-oriented process development and contributes to the reliable implementation of continuous fiber-reinforced additive manufacturing for future space structures.

1. INTRODUCTION

Continuous fiber-reinforced additive manufacturing (CF-AM) has emerged as a promising manufacturing approach for lightweight composite structures requiring high specific stiffness, functional integration, and geometric design freedom [1-7]. Compared with conventional laminate manufacturing, CF-AM enables the near-net-shape fabrication of complex geometries while reducing material waste and manufacturing effort [5,6]. These capabilities make the technology particularly attractive for future space structures, where stringent mass limitations, structural reliability, and qualification-oriented manufacturing are key design requirements.

Despite these advantages, the qualification of continuous fiber-reinforced additively manufactured components remains a major challenge [8-10]. Unlike conventional composite manufacturing, CF-AM combines filament production, impregnation, consolidation, and deposition into a highly coupled process chain. As a result, manufacturing-induced defects may accumulate throughout the process and significantly influence the final material quality and structural performance.

Among these defects, voids represent one of the most critical quality characteristics [1,3,7]. Numerous studies have demonstrated their detrimental influence on interlaminar strength, fatigue resistance, thermal conductivity, and long-term durability [1-4]. For space applications, these effects become even more significant due to demanding environmental conditions such as thermal cycling, vacuum exposure, radiation, and extended mission lifetimes. Consequently, qualification strategies require a comprehensive understanding of defect formation mechanisms rather than relying solely on global quality indicators.

Most existing studies evaluate manufacturing quality using the overall void content as the primary quality metric [1-5,7]. Although this parameter provides a general assessment of material quality, it neglects differences in void morphology, spatial distribution, and formation mechanisms. Consequently, similar global void fractions may result from fundamentally different manufacturing conditions and therefore cannot adequately explain variations in structural performance or identify the governing process parameters responsible for defect formation.

To overcome these limitations, a methodology for the differentiated characterization and analytical

description of void structures has been developed. The methodology combines systematic void subtype classification, image-based characterization, statistical regression, and physics-based analytical modelling to establish direct process–structure relationships and enable a mechanistic interpretation of void formation.
This paper presents the application of the proposed methodology to continuous fiber-reinforced thermoplastic filament systems with particular emphasis on its relevance for qualification-oriented manufacturing of space composite structures. Rather than introducing another defect characterization technique, the work demonstrates how defect-specific analysis can be used to identify governing process parameters, validate analytical models, and support reliable manufacturing and future qualification strategies for continuous fiber-reinforced additive manufacturing.

2. METHODOLOGY

2.1 Concept of the Methodology

Conventional quality assessment of continuous fiber-reinforced thermoplastic composites is predominantly based on the determination of the global void content. Although this parameter provides a quantitative measure of manufacturing quality, it does not differentiate between void morphologies, spatial distributions, or formation mechanisms. Consequently, comparable global void fractions may result from fundamentally different manufacturing conditions and cannot adequately describe the resulting material quality.
To address this limitation, a methodology for defect-oriented void characterization is proposed. Instead of treating voids as a homogeneous defect population, individual voids are classified according to their geometry, location within the composite architecture, and presumed formation mechanism. This differentiation enables defect-specific evaluation and establishes direct relationships between manufacturing conditions and characteristic void populations.
The methodology comprises four consecutive stages. First, representative filament cross-sections are prepared using standardized metallographic procedures. Subsequently, high-resolution optical microscopy and automated image processing are employed to detect and segment individual voids [11]. The segmented defects are then assigned to predefined void subtypes before subtype-specific statistical evaluation is performed. Finally, the experimental results are combined with regression analysis and physics-based analytical modelling to identify the governing mechanisms of void formation and establish transferable process–structure relationships.
In contrast to conventional empirical process optimization, the proposed methodology links experimental observations with physically interpretable descriptors. This enables a generalized assessment of impregnation quality that is largely independent of a specific machine configuration and therefore transferable to different material systems and manufacturing platforms.

2.2 Experimental Application

The proposed methodology was applied to continuous fiber-reinforced thermoplastic filaments manufactured under controlled laboratory conditions using the experimental setup shown in Figure 1. The manufacturing system enables controlled variation of the principal impregnation parameters while ensuring reproducible processing conditions throughout the experimental campaign.

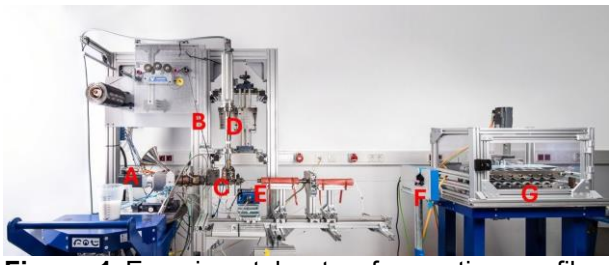


Figure 1 Experimental setup for continuous fiber filament manufacturing: (A) extruder, (B) fiber feed, (C) co-extrusion die, (D) ultrasonic transducer, (E) nozzle module, (F) inline measurement, (G) haul-off.

The experimental programme was designed to generate reproducible variations in impregnation quality while maintaining all remaining boundary conditions constant. Using the manufacturing system shown in Figure 1, processing temperature, consolidation pressure, fiber transport velocity, and ultrasonic excitation were systematically varied to investigate their influence on resin impregnation and void formation. The selected parameter combinations ensured stable manufacturing while generating representative void structures for subsequent analysis.
Following filament production, representative specimens were embedded, polished, and prepared for optical microscopy using a standardized preparation procedure.
The acquired micrographs formed the basis for the subsequent image analysis and void subtype classification. Each detected void was assigned to a predefined subtype prior to statistical evaluation, providing the experimental dataset required for the regression analyses and the validation of the analytical framework presented in the following sections.

3. APPLICATION OF THE METHODOLOGY

3.1 Void Subtype Identification

The application of the proposed methodology begins with the identification and classification of void structures generated during continuous fiber filament manufacturing. In contrast to conventional quality assessment based solely on the global void

fraction, the presented approach differentiates individual void populations according to their morphology, spatial location, and underlying formation mechanisms. This defect-oriented perspective enables a substantially more detailed interpretation of the manufacturing process and establishes the foundation for subsequent analytical evaluation.

Representative filament cross-sections were prepared following standardized preparation procedures and analysed using high-resolution optical microscopy. Automated image processing was subsequently employed to segment fibers, matrix, and void regions before individual defects were assigned to predefined void subtypes according to their geometric characteristics and position within the composite architecture, as illustrated in Figure 2. The classification procedure ensures objective and reproducible identification of defect populations while minimizing operator-dependent influences.

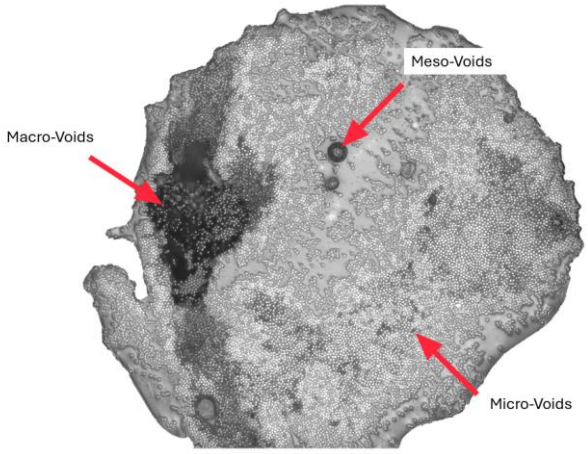


Figure 2 Classification of characteristic void subtypes.

The resulting subtype distributions reveal that comparable global void fractions may originate from fundamentally different manufacturing conditions. While the total void content provides a general indication of material quality, it does not distinguish between voids caused by insufficient fiber impregnation, incomplete consolidation, or local resin flow instabilities. Consequently, identical global quality indicators may represent considerably different defect mechanisms and therefore different implications for structural performance.

Representative examples of filament cross-sections with different impregnation qualities are shown in Figure 3. While homogeneous fiber distribution results in only small isolated voids, insufficient impregnation leads to non-uniform fiber distribution and the formation of pronounced dry regions within the fiber bundle.

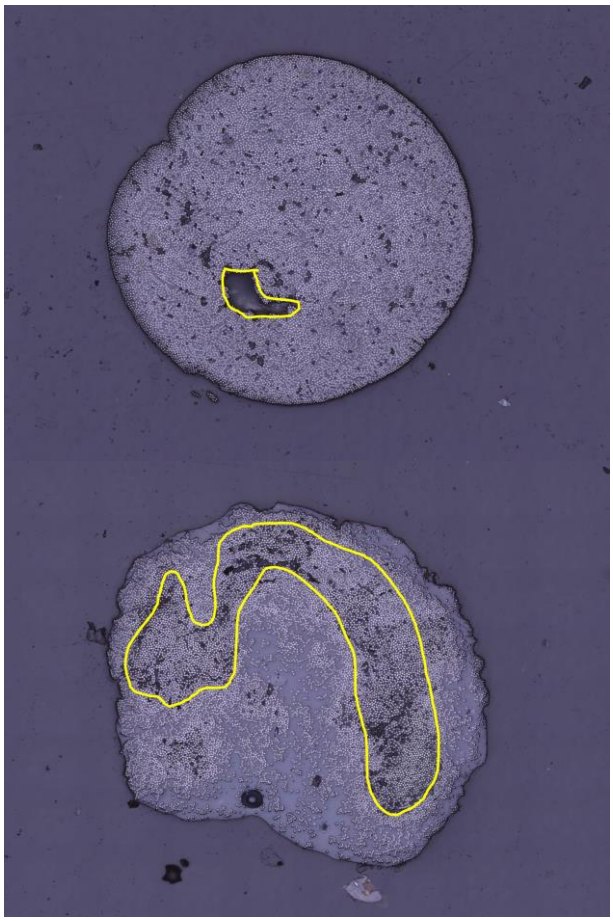


Figure 3 Representative filament cross-sections showing homogeneous (top) and insufficient (bottom) impregnation.

The proposed classification preserves this defect-specific information and enables a mechanistic interpretation of void formation. Instead of reducing manufacturing quality to a single scalar quantity, the defect population is transformed into a multidimensional dataset that forms the basis for statistical evaluation, analytical modelling, and process-specific interpretation.

3.2 Quantitative Image Analysis

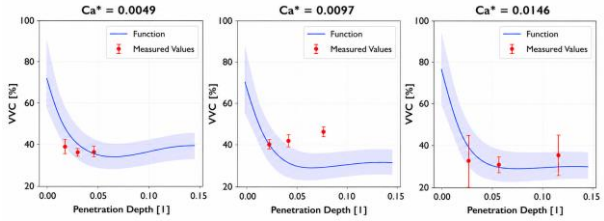
Following classification, each void subtype was quantitatively characterised using automated image analysis. Besides the number of voids, additional geometric descriptors including equivalent diameter, projected area, aspect ratio, and spatial distribution were determined for every manufacturing condition. This comprehensive characterization provides substantially more information than conventional void content measurements and enables a detailed comparison between different processing conditions.

To ensure statistical robustness, multiple cross-sections were evaluated for every experimental configuration, resulting in datasets comprising several thousand individual void objects. Rather than averaging all defects into a single quality parameter, subtype-specific distributions were analysed independently. This approach enables characteristic process signatures to be identified

and significantly improves the sensitivity of the evaluation.
The quantitative analysis demonstrates that manufacturing parameters affect individual void populations differently. Whereas certain parameter variations primarily influence intra-bundle impregnation defects, others predominantly affect voids located at the fiber–matrix interface or within matrix-rich regions. These observations indicate that void formation is governed by multiple interacting physical mechanisms rather than a single dominant process.
The resulting datasets provide the experimental basis for establishing statistically robust process–structure relationships. In the next step, subtype-specific regression analyses are performed to quantify the influence of individual manufacturing parameters on the observed void populations.

3.3 Statistical Correlation of Process Parameters

The quantified void subtype distributions were subsequently correlated with the investigated manufacturing parameters to identify the dominant mechanisms governing void formation. Rather than establishing empirical relationships for the overall void content, regression analyses were performed separately for each void subtype [12]. This defect-specific evaluation enables individual process influences to be distinguished and significantly improves the interpretability of the resulting models.
The statistical analysis revealed that the investigated process parameters exhibit markedly different sensitivities depending on the respective void subtype. Consolidation pressure predominantly influences inter-fiber impregnation by enhancing polymer infiltration into the fiber bundle, resulting in a significant reduction of impregnation-related voids. In contrast, processing temperature primarily affects resin viscosity and flow behaviour, thereby influencing matrix-associated defects generated during consolidation. Fiber transport velocity controls the available impregnation time and consequently governs the development of characteristic void morphologies throughout the manufacturing process. Representative regression models are shown in Figure 4.



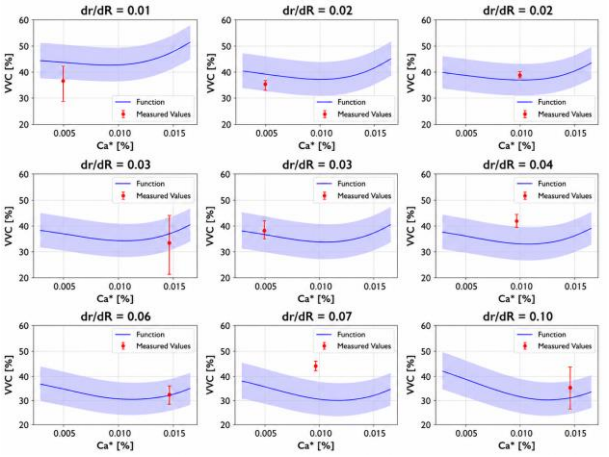


Figure 4 Regression models for predicting characteristic void subtype distributions.

The independent evaluation of individual void populations demonstrates that void formation cannot be attributed to a single governing process parameter. Instead, the observed defect structures result from the interaction of multiple transport, wetting, and consolidation mechanisms acting simultaneously during filament production. This observation explains why manufacturing conditions producing comparable global void fractions may nevertheless exhibit substantially different defect morphologies and, consequently, different structural properties.
Compared with conventional quality assessment based solely on the overall void content, the subtype-specific regression approach considerably increases the sensitivity of process evaluation. Parameter interactions that remain concealed within global quality indicators become directly identifiable when analysed on the level of individual defect populations. The statistical framework therefore enables process signatures to be extracted from the experimental data and provides a quantitative basis for interpreting defect evolution.
Beyond the statistical significance of individual parameter correlations, the regression models provide the experimental foundation for the analytical framework introduced in the following section. While regression analysis identifies which manufacturing parameters govern individual void populations, it does not explain why these relationships exist. Addressing this limitation requires a physics-based description of the impregnation process, allowing the experimentally observed correlations to be interpreted in terms of the governing flow and wetting mechanisms.

3.4 Analytical Prediction of Void Formation

Although the regression models presented in the previous section provide accurate predictions within the investigated process window, their applicability remains limited to the experimentally observed parameter space. To extend the methodology beyond empirical correlations, a physics-based analytical framework was developed that describes

the governing mechanisms of resin impregnation and void formation.
The analytical approach is based on the interaction between viscous resin flow, capillary forces, impregnation time, and the permeability of the continuous fiber bundle [13-15]. Instead of interpreting manufacturing behaviour solely through machine-specific parameters such as processing temperature, consolidation pressure, or fiber transport velocity, these influences are transformed into physically meaningful descriptors that characterize the impregnation process independently of a particular manufacturing system. The relationship between statistical regression and the analytical framework is illustrated in Figure 5. While regression analysis identifies statistically significant process influences, the analytical model provides a physics-based interpretation of the governing impregnation mechanisms and enables the prediction of void subtype formation beyond the investigated experimental conditions.

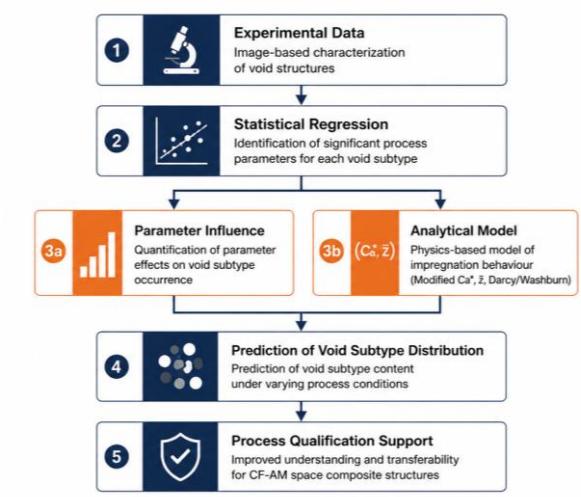


Figure 5 Combined statistical and analytical framework for void prediction.

A central element of the analytical framework is the modified capillary number, which represents the balance between viscous flow and capillary forces during resin infiltration [13-15]. Together with the normalized impregnation depth, describing the penetration of the polymer melt into the fiber bundle, these dimensionless parameters provide a unified representation of the governing impregnation mechanisms [13-15]. Consequently, manufacturing conditions that differ in machine settings or material combinations can be evaluated within the same physical framework.
The calculated analytical descriptors were correlated with the experimentally determined void subtype distributions. The results demonstrate that process conditions exhibiting comparable analytical characteristics also generate similar defect populations, despite differences in the individual manufacturing parameters. Compared with purely empirical regression models, the analytical framework therefore provides a substantially improved physical interpretation of the observed defect evolution.
The transformation from machine-specific process parameters to dimensionless physical descriptors represents one of the principal contributions of the proposed methodology. Rather than describing manufacturing behaviour exclusively through experimental observations, the approach establishes a mechanistic relationship between impregnation physics and defect formation. This significantly improves the transferability of manufacturing knowledge across different equipment configurations, material systems, and processing conditions.
By combining statistical regression with analytical modelling, the methodology links experimental observations with the underlying physical mechanisms governing void formation. While regression analysis identifies which process parameters influence individual void populations, the analytical framework explains why these relationships occur. The resulting combination provides a predictive basis for process optimisation and qualification-oriented manufacturing of continuous fiber-reinforced thermoplastic composites.

3.5 Validation of the Methodology

The predictive capability of the proposed methodology was evaluated by comparing analytically derived process descriptors with experimentally determined void subtype distributions obtained under different manufacturing conditions and material configurations. Rather than validating individual regression models alone, the objective was to assess whether the combined statistical and analytical framework consistently captures the governing mechanisms of void formation.
For each experimental configuration, the analytical descriptors were calculated from the measured manufacturing parameters and compared with the corresponding void subtype distributions obtained from microscopic image analysis. The comparison between measured and regression-predicted total void contents for the PPS/AS7 material system is presented in Figure 6. Overall, a good agreement between predicted and experimentally observed defect characteristics was achieved, demonstrating that the proposed framework adequately represents the dominant impregnation mechanisms responsible for void evolution.

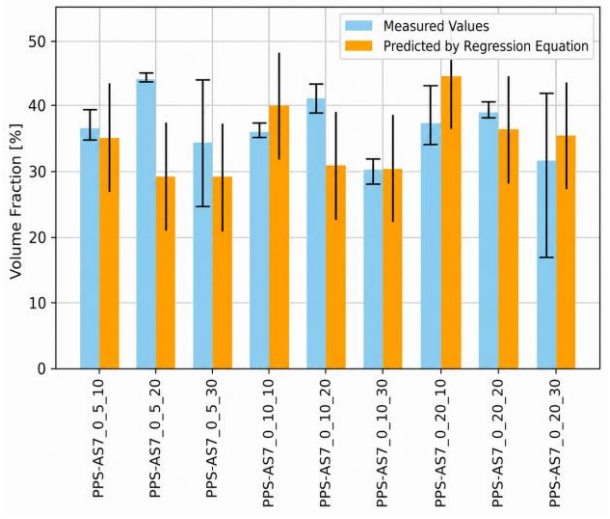


Figure 6 Comparison of measured and regression-predicted total void content (VVC) for PPS/AS7 filaments under different processing conditions. Error bars represent the experimental standard deviation (measured values) and the regression model uncertainty (RMSE) (predicted values). Sample names follow the format: polymer–fibre–ultrasonic influence – fibre velocity (mm s^{-1}) – impregnation pressure (bar).

4. APPLICATION OF THE METHODOLOGY TO SPACE STRUCTURES

4.1 Relevance of Void Characterization for Space Structures

Continuous fiber-reinforced thermoplastic composites are increasingly being considered for lightweight structural components in satellites, launch vehicles, and spaceborne support structures due to their high specific stiffness, corrosion resistance, and potential for functional integration [8-10]. In combination with additive manufacturing, these materials offer new design opportunities by enabling near-net-shape fabrication of highly integrated components while reducing manufacturing waste and assembly effort.

Despite these advantages, qualification remains one of the principal barriers to the adoption of continuous fiber-reinforced additive manufacturing for space applications [8-10]. Unlike conventionally manufactured composite laminates, the mechanical performance of additively manufactured structures is strongly influenced by process-dependent microstructural features generated throughout the manufacturing chain. Consequently, reproducible manufacturing quality is a prerequisite for reliable structural performance.

Among the various manufacturing-induced defects, voids represent one of the most critical microstructural features because they influence not only static strength but also fatigue behaviour, thermal conductivity, damage tolerance, and long-term durability [1-4]. Under representative space environmental conditions—including thermal cycling, vacuum exposure, and extended mission durations—localized defects may act as initiation sites for progressive degradation and premature structural failure [8-10].

Conventional qualification strategies therefore require more than the determination of the global void fraction. A detailed understanding of defect morphology, spatial distribution, and formation mechanisms is required to evaluate the relationship between manufacturing conditions and structural reliability. The methodology presented in this work addresses this requirement by linking characteristic void populations directly to the governing impregnation mechanisms and associated manufacturing parameters.

Rather than serving exclusively as a post-process inspection method, the proposed framework enables defect-informed process evaluation and supports qualification-oriented manufacturing by providing a physically interpretable description of defect formation. Figure 7 summarizes how the methodology links manufacturing parameters with defect evolution, local material properties, structural performance, and ultimately process qualification.

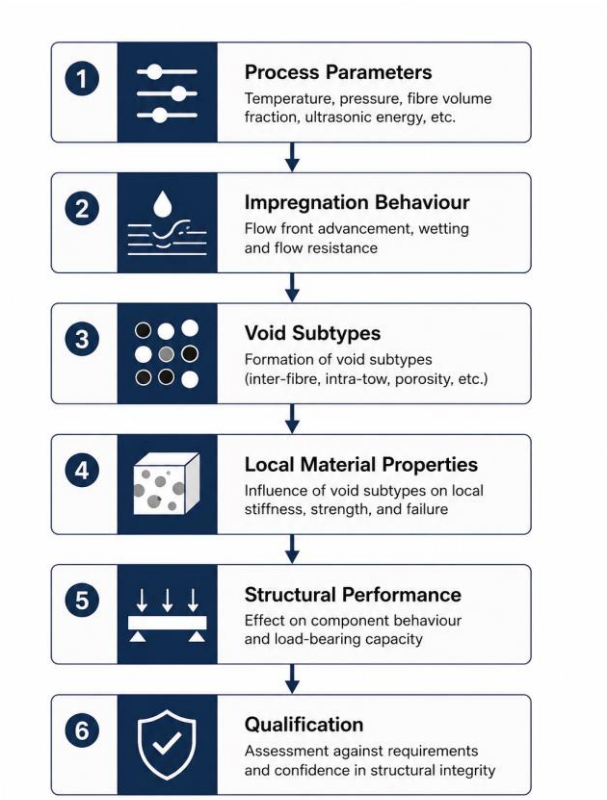


Figure 7 Process–structure–qualification framework of the proposed methodology.

4.2 Contribution to Process Qualification

The principal contribution of the proposed methodology lies in its ability to transform experimentally observed defect populations into transferable manufacturing knowledge. Instead of evaluating composite quality only after production, the methodology establishes quantitative relationships between manufacturing parameters,

impregnation behaviour, and resulting void subtype distributions. This enables process conditions to be assessed according to their expected influence on structural quality before extensive experimental validation is performed.
Within qualification campaigns, this information facilitates the identification of stable manufacturing windows by distinguishing parameter variations that primarily generate non-critical defect populations from those promoting structurally relevant void mechanisms. Consequently, process optimisation can focus on the physical origin of manufacturing defects rather than on global quality indicators alone.
An additional advantage is the use of dimensionless analytical descriptors describing the governing impregnation mechanisms independently of a particular manufacturing platform. Since these descriptors retain their physical interpretation across different equipment configurations and material systems, manufacturing knowledge generated during process development can be transferred more efficiently to future production environments.
Although application-specific validation remains necessary for each qualified component, the presented methodology significantly reduces the experimental effort required during process optimisation. The framework therefore represents a valuable tool for qualification-oriented manufacturing development, where reproducibility, traceability, and process understanding are essential requirements.

4.3 Transferability to Future Space Manufacturing

Although the methodology has been developed using continuous fiber-reinforced thermoplastic filament manufacturing, its underlying concept is not restricted to the investigated process. Because the analytical framework is derived from fundamental impregnation mechanisms and validated through statistically robust defect characterization, the methodology can be transferred to other continuous fiber manufacturing technologies with only minor adaptations.
Potential application fields include automated fiber placement with in-situ consolidation, robotic continuous fiber deposition, hybrid additive manufacturing processes [5-7], and future in-space manufacturing concepts, where process robustness and resource efficiency are expected to become key enabling technologies [8-10].
Beyond the investigated manufacturing process, the proposed methodology establishes a general framework for linking manufacturing conditions with microstructural defect evolution and resulting material quality. This systematic process–structure description provides a suitable basis for future digital qualification workflows combining experimental characterization, analytical modelling, numerical simulation, and process monitoring. The envisioned development pathway of the methodology towards predictive and qualification-oriented manufacturing is illustrated in Figure 8.

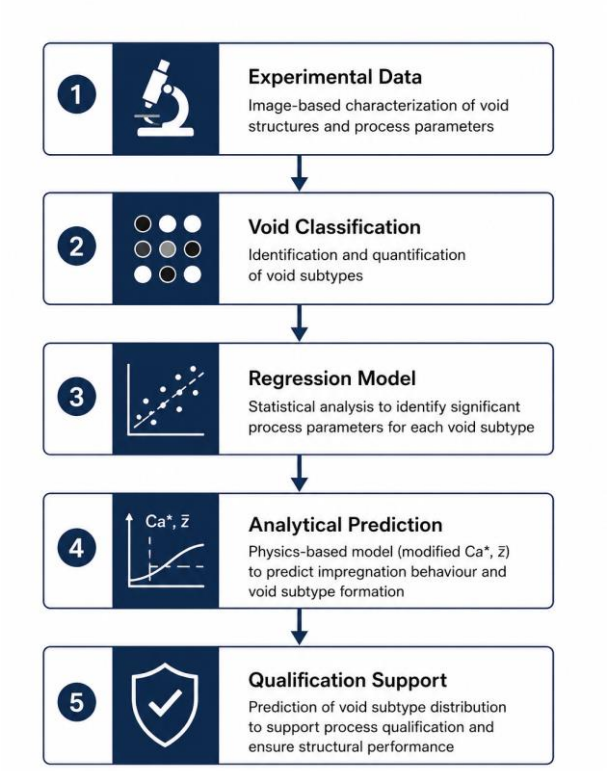


Figure 8 Roadmap towards predictive and qualification-oriented manufacturing of continuous fiber-reinforced composite structures.

Future developments should therefore focus on integrating the methodology with non-destructive evaluation techniques, in-situ monitoring systems, and digital twin concepts. Combined with representative environmental testing under space conditions, these extensions have the potential to establish qualification-oriented manufacturing strategies for continuous fiber-reinforced composite structures used in future space missions.

5. DISCUSSION

The results presented in this work demonstrate that a defect-oriented evaluation of void structures provides substantially more information than conventional quality assessment based solely on the global void fraction [5,6]. By differentiating individual void subtypes and relating them to their governing formation mechanisms, the proposed framework enables manufacturing quality to be interpreted on the basis of process physics rather than empirical quality indicators. This represents a fundamental shift from retrospective defect assessment towards process-oriented quality evaluation.
A key outcome of the investigation is that manufacturing conditions exhibiting comparable global void fractions may generate fundamentally different defect populations. Consequently, identical

global quality indicators cannot be assumed to represent equivalent structural behaviour. The presented methodology addresses this limitation by preserving defect-specific information throughout the evaluation process and establishing direct process–structure relationships between manufacturing conditions and characteristic void morphologies.

Another important contribution is the integration of experimental characterization with statistical evaluation and physics-based analytical modelling. Whereas regression analysis identifies statistically significant relationships between manufacturing parameters and void subtype distributions, the analytical framework provides a mechanistic explanation of the governing impregnation processes. The combination of both approaches extends the applicability of the methodology beyond empirical parameter optimisation and establishes a transferable framework that is largely independent of a specific manufacturing platform.

From a manufacturing perspective, this considerably improves process development by enabling manufacturing knowledge to be transferred between different equipment configurations, material systems, and processing conditions. Instead of generating isolated empirical datasets for individual manufacturing setups, the proposed framework provides generalized process descriptors that retain their physical interpretation across different applications.

For qualification-oriented manufacturing of space structures, this capability is particularly relevant. Future qualification concepts require not only reproducible manufacturing quality but also traceable relationships between manufacturing conditions, defect evolution, and structural performance [8-10]. By combining systematic defect characterization with analytical process modelling, the proposed methodology contributes to the development of physically interpretable qualification strategies for continuous fiber-reinforced additive manufacturing.

Nevertheless, several limitations should be considered. The present investigation is based on laboratory-scale continuous fiber-reinforced thermoplastic filament manufacturing and therefore represents a controlled manufacturing environment. Although the analytical concepts are transferable, additional validation is required for complete additively manufactured components, alternative impregnation technologies, and different thermoplastic material systems. Furthermore, the methodology currently relies on post-process characterization and therefore does not yet provide real-time assessment of manufacturing quality.

The future development of the proposed methodology is summarized in Figure 9. Building upon the experimental and analytical framework presented in this work, future developments aim to integrate inline monitoring, digital twins, and predictive qualification concepts into a unified process qualification strategy.

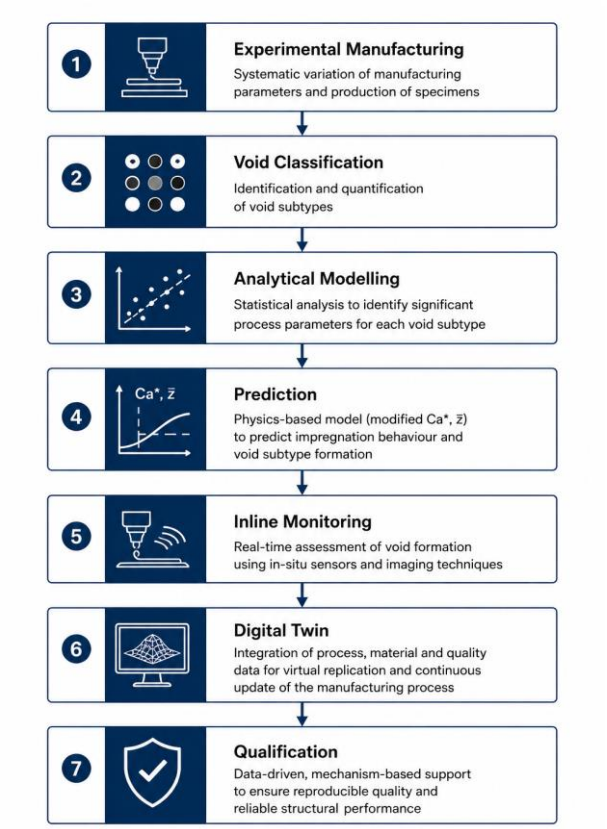


Figure 9 Future development roadmap of the proposed methodology towards predictive process qualification and digital manufacturing of continuous fiber-reinforced composite structures

Future research should therefore focus on extending the proposed framework towards in-situ process monitoring and digital qualification concepts. The integration of optical inspection systems, X-ray computed tomography, machine learning-assisted defect recognition, and process simulations has the potential to establish predictive quality assessment during manufacturing. Combined with digital twin approaches and representative environmental testing, these developments could significantly improve qualification methodologies for continuous fiber-reinforced composite structures used in future space missions.

6. CONCLUSIONS

This paper presented the application of a methodology for the differentiated characterization, analysis, and prediction of void structures in continuous fiber-reinforced thermoplastic composite filaments. By combining systematic void subtype classification with automated image analysis, statistical regression, and physics-based analytical modelling, the proposed framework establishes transferable process–structure relationships that extend beyond conventional void content evaluation.

The results demonstrate that defect-specific characterization provides significantly greater insight into manufacturing quality than global void fraction alone. Individual void subtypes were shown to respond differently to variations in processing conditions, allowing the governing impregnation mechanisms to be identified and interpreted within a unified analytical framework. The combination of statistical evaluation and physically based process descriptors therefore enables both quantitative prediction and mechanistic understanding of void formation.

From a manufacturing perspective, the proposed methodology transforms experimental observations into transferable process knowledge. The use of dimensionless analytical descriptors enables manufacturing behaviour to be compared across different material systems and equipment configurations, reducing the dependence on machine-specific empirical optimisation and supporting more efficient process development.

For qualification-oriented manufacturing of future space structures, the presented framework provides a structured approach for linking manufacturing parameters, defect evolution, and resulting material quality. Although further validation on complete components and under representative space environmental conditions is required, the methodology establishes an important foundation for predictive process qualification of continuous fiber-reinforced additive manufacturing.

Future work will focus on extending the framework towards complete additively manufactured structures, integrating non-destructive inspection techniques and inline process monitoring, and coupling the methodology with digital twins and qualification workflows. These developments have the potential to enable data-driven, physics-based qualification strategies for next-generation lightweight composite structures in space applications.

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