Research Article

Optimization of Pultrusion Process Parameters for Carbon Fiber/Epoxy Composites

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Abstract

This study investigates the effects of key pultrusion process parameters—including temperature profile, fiber volume ratio (FVR), preformer geometry, resin viscosity, and line speed—on the production stability and mechanical performance of carbon fiber/epoxy composite profiles. Continuous carbon fiber rovings were impregnated with epoxy resin and processed through a multi-zone heated die under varying operating conditions. Tensile properties were evaluated in accordance with ASTM D3039 to ensure standardized and comparable mechanical characterization. Experimental observations revealed that even small adjustments in thermal management, heating zone positioning, preformer compression and eye diameter, fiber volume ratio, resin rheology, fiber type, squeezer configuration, and pulling speed produced significant variations in surface quality, flow behavior, resin backflow, fiber congestion, and overall process stability. The optimal process window was achieved at a line speed of 30–35 cm/min and an FVR range of 65–70%, with improved results obtained by shifting the initial heating zone backward, reducing the final preformer diameter, and utilizing lower-viscosity resin systems. The findings provide a comprehensive process–property relationship for carbon pultrusion and offer a practical *guideline for industrial optimization aimed at achieving stable production and high-quality composite profiles.*

Keywords: Pultrusion, Carbon Fiber Reinforced Polymer (CFRP), Optimization

1. Introduction

Composite materials are among the most important engineering materials. Due to their superior mechanical properties—such as strength, impact resistance, and stiffness—compared to many conventional materials, and their significantly lower weight, they are increasingly preferred as alternatives to traditional materials. Their areas of application continue to expand not only in defense and aerospace, but also in other sectors such as automotive and construction. Therefore, research on composite manufacturing methods and the enhancement of composite material properties is growing rapidly.

Composite materials are typically classified based on their reinforcement and matrix components, and the choice of manufacturing method depends on criteria such as the target product geometry, required mechanical properties, and cost. For example, pultrusion is preferred for long, continuous profiles requiring continuous fiber reinforcement, whereas filament winding is considered more suitable for tanks or pipes with circular geometries [1]. Within this wide range of applications, pultrusion stands out as one of the most efficient methods for the mass production of continuous fiber–reinforced polymer matrix profiles. The pultrusion process is based on impregnating continuous fibers with resin and pulling them through a heated die for curing. Its high production rate, automation capability, and ability to achieve high fiber volume fractions make the method extremely economical for constant cross-section profiles. The continuous nature of pultrusion differentiates it from other composite manufacturing techniques and provides a significant competitive advantage, particularly for industries requiring large-scale serial production.

Two primary resin impregnation approaches are used in pultrusion: the open-bath system and the closed injection–impregnation chamber (ii-chamber). For highly reactive thermoset resins and reactive thermoplastics requiring in-situ polymerization, the ii-chamber provides more controlled flow and more homogeneous wet-out. However, FVM-based simulations demonstrated the presence of low-flow regions—referred to as "dead zones" inside the ii-chamber, where resin begins to partially cure, leading to accumulation on mold walls and surface defects. These findings help explain industrial problems such as white powder formation, resin burning, and preformer clogging.

In recent years, interest in reactive and melt-processed thermoplastic pultrusion has increased. Thermoplastic matrix composites offer advantages such as high impact resistance, recyclability, and post-formability. However, the industrial use of thermoplastic pultrusion remains limited, mainly due to high temperature requirements, viscosity management challenges, and complex heat transfer behavior [2].

One of the major challenges in the pultrusion process is the inability to monitor the cure reaction in real time. Traditional dielectric sensors and fiber-optic techniques cannot operate for extended periods due to the abrasive environment inside the pultrusion die. To overcome this limitation, developed the Resonant Ultrasonic Spectroscopy (RUS) technique, which enables continuous cure monitoring inside a closed pultrusion die. The RUS method detects changes in acoustic impedance during curing and can determine the gel point and glass transition temperature with high accuracy, thereby allowing closed-loop control of process parameters such as line speed and die temperature [3].

This study aims to integrate the findings reported in the literature regarding pultrusion processes with field observations obtained from the production line, including surface defects, resin flow behavior, preformer clogging, and the effects of temperature profiles. In doing so, it seeks to establish a comprehensive roadmap for optimizing process parameters to achieve a more stable, cost-effective, and high-quality pultrusion process.

2. Pultrusion

Pultrusion is one of the most widely used methods for manufacturing continuous fiber–reinforced composite profiles, as it provides high repeatability, low material waste, and uninterrupted production capacity in large-volume manufacturing. Due to its energy efficiency, low labor requirements, and high level of automation, it stands out as a cost-effective and environmentally friendly production technique [4]. The method has become a standard in the industry, particularly for combining thermoset resins such as epoxy, vinyl ester, and polyester with glass, carbon, and aramid fibers.

Pultrusion is a manufacturing process used to produce CFRP materials in continuous lengths and various cross-sectional geometries. A schematic representation of the pultrusion method is shown. The raw materials include a liquid resin mixture—typically epoxy or polyurethane-based—as the matrix, and reinforcing carbon fibers.

The scientific foundations of the pultrusion process have been progressively developed since the 1950s. As noted by Jaklitsch, Bostic, and Pattie [5], pultrusion is “a process that appears simple yet exhibits complex behavior due to the strong interdependency of its parameters.” Similarly, Chachad and colleagues [6] emphasized that pultrusion is not merely a mechanical pulling operation, but a sophisticated manufacturing process that requires simultaneous management of three-dimensional heat transfer, exothermic cure kinetics, and fiber–resin interactions.

In industrial practice, the pultrusion process is typically described in four stages:
(1) fiber feeding,

(2) resin impregnation (wet-out),
(3) shaping and curing within the heated die,
(4) pulling and cutting.

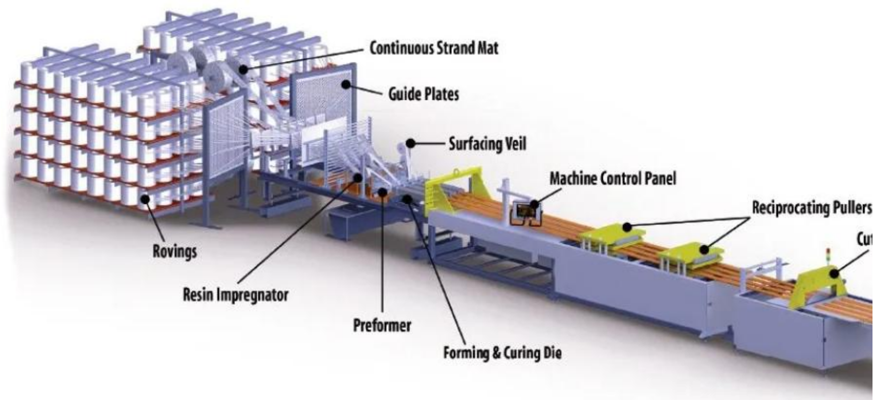

Figure 1. Pultrusion Process (2025)

The following sections present these stages integrated with findings from the literature and field observations.

Fiber Feeding and Preforming

Continuous fiber rovings are fed from the creel system into the preformer unit under controlled tension. Proper fiber alignment is one of the most critical stages of pultrusion. Studies shows that when fiber tension falls below a certain minimum threshold, defects such as ballooning, fiber accumulation, and even die blockage can occur at the preformer and die entrance [5].

On the other hand, excessive tension does not improve mechanical properties; instead, it complicates the threading operation and reduces the system's tolerance to changes in line speed and temperature [5]. Therefore, fiber tension is considered a parameter that is critical not for mechanical performance but for process stability.

Resin Impregnation and Viscosity Control

The fibers then enter an epoxy–anhydride-based resin bath. During the resin impregnation stage, viscosity is the main parameter that governs fiber wetting behavior and the amount of resin carried out of the bath. High viscosity impedes resin transport between the fibers and increases internal pressure, potentially leading to "bird-nesting" [5].

Low surface tension in epoxy systems increases the capillary number, and as a result, wetting becomes largely independent of line speed [6].

In industrial applications, pigment, UV stabilizer, accelerator, or catalyst may be added to the resin. These additives directly influence outdoor durability, color stability, and curing rate of the final product.

Heated Die: Curing, Heat Transfer, and Line Speed Interaction

The heated die represents the most complex stage of the pultrusion process. Inside the die, three simultaneous phenomena occur:

1. heat conduction,
2. exothermic chemical reaction (curing),
3. shaping and directing of resin flow.

The relationship between line speed and die temperature is “an inseparable pair,” meaning that physical heat transfer and chemical curing cannot be decoupled. Low line speeds cause early gelation and surface defects, while excessively high speeds lead to undercured regions and mechanical weaknesses [5]. Through three-dimensional modeling of heat distribution in the die, demonstrated that the optimal gel point should generally occur within the final one-third of the die length [6].

If die temperature is too low, poor surface quality results; if too high, internal cracking and irregular exothermic reactions may occur. Additionally, cooling the die entrance region is recommended to prevent premature resin gelation [11].

Heated Die: Curing, Heat Transfer, and Thermo-Chemical Modeling

The most complex stage of the pultrusion process consists of the simultaneous heat transfer, curing reaction, and shaping steps experienced by the fiber–resin mixture as it passes through the heated die. At this stage, physical and chemical phenomena are inseparably coupled. Studies emphasized that heat diffusion within the die and the exothermic curing reaction constitute an “inseparable pair,” and thus line speed and die temperature must be considered together [5].

The study demonstrated that pultrusion is not only governed by machine parameters but also represents a multiphysics problem requiring simultaneous control of the three-dimensional thermal field, cure rate, viscosity evolution, and internal heat generation. In modern literature, pultrusion is often represented through coupled equations of heat transfer and cure kinetics [6].

The general mathematical model used for this purpose is expressed as follows:

$$\rho c\left(\frac{\partial T}{\partial t} + u\frac{\partial T}{\partial x}\right) = \nabla \cdot (\bar{\mathbf{k}}T) + q \qquad (1)$$

$$\frac{\partial \alpha}{\partial t} + u\frac{\partial \alpha}{\partial x} = R_r(\alpha, T) \qquad (2)$$

In this equation set:

T denotes the temperature;
u represents the pulling speed;
ρ is the density;
c is the specific heat;
$\bar{k}$ refers to the thermal conductivity tensor of the material;
q indicates the exothermic internal heat generation arising from resin curing;
α denotes the degree of cure; and
R_r(α, T) represents the reaction rate of the resin as a function of temperature and degree of cure.

This model provides a widely used framework for predicting the temperature profile and cure distribution along the pultrusion line. Equation (1) describes heat convection–conduction and the exothermic heat generation, whereas Equation (2) explains how the resin cures as a function of time and position. In this way, the effects of parameters such as pulling speed, die temperatures, resin type, and fiber volume ratio on the actual physical behavior inside the die can be examined numerically.

This mathematical approach is critically important for process optimization in industry, as the correct formation of the gel point within the die, the reduction of surface defects, the control of resin backflow, and the complete curing of the product can only be achieved through such multiphysics analyses [3].

Die Exit, Detachment, and Cutting
As the curing reaction progresses, the temperature of the composite material exceeds the die temperature, and at this stage, the profile begins to detach naturally from the die surface. This natural detachment behavior enables the formation of a smooth surface finish. The product is continuously pulled by the pulling units, and in the final stage, it is cut to the desired lengths with a saw, completing the process.

3. Composite Materials

Composite materials are multiphase engineering materials formed by the combination of two or more chemically and/or physically distinct phases at the macroscopic scale. The fundamental constituents of these materials are the reinforcement phase, which carries the load, and the matrix phase, which shapes the performance characteristics.

The classification of composites is generally based on the origin of the reinforcement, the type of matrix, and the morphology of the reinforcement. The first classification axis distinguishes between natural fiber composites and synthetic fiber composites, primarily based on parameters such as sustainability and cost. Natural fibers (e.g., jute, sisal, flax) offer environmental advantages but have limitations such as mechanical instability and moisture sensitivity; in contrast, synthetic fibers such as carbon, glass, and aramid provide superior mechanical properties and high strength-to-weight ratios.

Another commonly used classification approach is based on the matrix phase, whereby composites are grouped into three main categories: polymer matrix composites (PMC), metal matrix composites (MMC), and ceramic matrix composites (CMC). Polymer matrix composites have the broadest application range—particularly in the automotive, defense, and aerospace sectors—due to their low density, high specific strength, and processing advantages. Polymer matrices are further subdivided into thermosets (e.g., epoxy, polyester) and thermoplastics (e.g., PP, PA, PEEK).

MMCs, on the other hand, are developed for applications requiring high temperature resistance, good thermal stability, and wear resistance. CMCs are preferred in applications operating above 1500 °C, where they maintain dimensional stability even under extreme conditions, particularly in energy, space, and high-temperature structural environments.

Finally, composites are also classified based on reinforcement geometry into particle-reinforced composites, short-fiber-reinforced composites, and continuous-fiber-reinforced composites. Continuous fiber–reinforced systems are of critical importance in advanced engineering applications due to their high anisotropic strength and the precise control they offer over fiber orientation [7].

To produce composite materials, reinforcements such as carbon and glass are typically used in the form of fibers or fabrics, while epoxy or vinyl ester resins are commonly employed as the matrix [8]. Although various manufacturing methods exist—such as hand lay-up, vacuum infusion, RTM, and pultrusion—these techniques are fundamentally based on the same principle. By combining the fiber and resin through the application of pressure or heat, a new material is created. This newly formed material is referred to as a fiber-reinforced polymer, or more generally, a composite material.

Fiber-reinforced polymer matrix composites are widely used in many engineering applications, and researchers continue to explore methods to enhance and improve their mechanical and physical properties. Numerous studies have examined the effects of such improvements. While hybridization of carbon and glass fibers can enhance certain mechanical properties of composite materials—such as tensile strength, flexural strength, elastic modulus, stiffness, and structural stability—it has also been reported by various researchers that negative effects may occur in terms of elongation at break, impact resistance, and toughness. Fiber-reinforced composite materials are preferred in the marine industry due to the superior properties they offer and are used in applications ranging from boat and vessel manufacturing to fishing rods. Impact behavior is an essential topic of investigation for composite materials, as different damage mechanisms and their interactions can lead to material failure. Composite plates produced by laminating unidirectional carbon fibers with a polymer-based resin through the pultrusion process are referred to as carbon plates [9].

2. Materials and Methods

This section presents in detail the pultrusion process parameters used in the study, including the fiber reinforcement, matrix system, preformer geometry, die temperature profile, and pulling speed. In the pultrusion process, both material selection and processing parameters directly influence the final product quality. The literature particularly emphasizes that resin flow, fiber wetting, ii-chamber geometry, and die temperature play decisive roles in determining surface defects and process stability [10]. Moreover, in thermoset pultrusion processes, the progression of the cure reaction and its relationship with line speed and die temperature is of critical importance; this interaction has been thoroughly demonstrated through RUS-based measurements [4].

Within the scope of this study, carbon fiber–epoxy systems were utilized to evaluate the effects of different preformer compaction ratios, resin formulations, and pulling speeds on production performance. Surface defects observed during manufacturing, resin backflow behavior, and blockage issues were systematically examined throughout the process. The aim of the study is to determine the optimal operating conditions that enhance process stability and product quality, taking into account the material properties and the technical parameters of the production line.

The reinforcement materials used in this study consisted of Tansome continuous carbon fiber rovings, which was selected after preliminary screening of multiple commercial rovings. Although several alternative carbon fiber products were evaluated during the early trials, Tansome fibers demonstrated notably superior performance with respect to filament integrity, tow stability during preforming, and resistance to breakage at the die entrance. These characteristics contributed to more uniform impregnation and reduced sensitivity to variations in pulling speed, leading to its exclusive use in the optimized manufacturing window.

The matrix phase employed Huntsman Araldite epoxy resin, selected based on its favorable rheological profile, stable cure behavior, and compatibility with high fiber volume fraction (FVR) configurations. While other epoxy formulations from other suppliers were also examined during preliminary testing, these systems exhibited higher flow resistance under pressure, greater sensitivity to temperature fluctuations, and a higher tendency to accumulate within the preformer region under elevated FVR conditions. Owing to these limitations, only the Huntsman epoxy system was retained for the final optimization trials.

Die lubrication during processing was achieved using Henkel Loctite 770-NC, which provided reliable internal release performance without introducing surface contamination or affecting composite cure kinetics.

2.1.Method

This study was carried out through a systematic series of experimental investigations designed to evaluate the influence of critical process parameters on the pultrusion of carbon fiber/epoxy composite profiles. The overall methodology was structured into three main stages: selection and preparation of materials, controlled pultrusion manufacturing trials under varying process conditions, and mechanical characterization of the produced composites.

2.1.1. Material Preparation

Multiple carbon fiber roving types from different manufacturers were initially evaluated to identify a reinforcement that offered stable handling, low filament breakage, and consistent wet-out under varying pultrusion conditions. Among these, Tansome roving exhibited superior performance, with significantly reduced filament damage during preforming and enhanced stability at the die entrance. As a result, Tansome was selected as the primary reinforcement in all optimized trials.

Similarly, several epoxy formulations were screened to determine their suitability for high-FVR pultrusion applications. Huntsman Araldite epoxy was selected due to its controlled viscosity range (500–900 mPa·s at 25 °C), stable cure kinetics, and favorable interaction with continuous carbon fibers. Other epoxy systems evaluated during screening were not retained because they exhibited issues such as elevated flow resistance, preformer-region accumulation, and increased sensitivity to process-induced pressure variations.

The internal release system employed exclusively Henkel Loctite 770-NC, which ensured effective lubrication of the die walls and prevented premature sticking or surface defects. No external release agents were used in the final trials.

2.1.2. Pultrusion Manufacturing Trials

All experiments were performed on an industrial-scale pultrusion line. Carbon fiber rovings were fed from the creel and guided through a three-stage preforming sequence, designed as follows:

- 1st preformer: 5 mm (≈180% compaction)
- 2nd preformer: 7 mm (≈140% compaction)
- 3rd preformer: 5.5 mm (≈115% compaction)
- Die cross-section: 100%
- Rod molds covered a range of 4.5–24 mm.

A later refinement suggested by tooling suppliers and verified experimentally involved reducing the final preformer diameter to 5.2 mm, which further minimized fiber flotation and congestion at higher pulling speeds.

Thermal Process Adjustments

Initial trials identified premature gelation and “white-powder” formation at the die entrance when the first heating zone was positioned too close to the die. To mitigate this effect, the first heating zone was shifted 15 cm backward, decreasing the entrance temperature and delaying gelation to a more controlled region within the die. This adjustment significantly improved surface quality and reduced thermal defects.

Temperature profiles of 155–180–180 °C and 200–200–220 °C were evaluated, depending on resin reactivity and pulling speed.

Kinematic and FVR Variations

Pulling speeds ranging from 18 to 45 cm/min were tested, alongside fiber volume ratios of 65–72%. Stable consolidation and uniform impregnation were observed at:

- Pulling speed: 30–35 cm/min
- FVR: 65–70%

Pulling speeds above 40 cm/min and FVR values near 72% produced local pressure spikes, resin backflow, and fiber congestion in the preformer region.

A total of more than 15 full-scale production trials were completed across rod diameters and process configurations.

2.1.3. Mechanical Testing

Mechanical characterization was conducted according to ASTM D3039, using both rod-type specimens and plates. Specimens manufactured under optimized process conditions—using Tansome fibers, Huntsman epoxy, and the corrected heating profile exhibited tensile strengths up to ~2300 MPa for plate specimens. Rod specimens demonstrated improved consistency and higher tensile strengths relative to early trials performed with non-optimized conditions or alternative resin systems.

All specimens were cut to the standard dimensions, tabbed, and tested on a universal testing machine under axial loading. Tensile strength and elastic modulus values were obtained and correlated with the corresponding process parameters to quantify the effects of pultrusion conditions on mechanical performance.

Through this integrated methodology encompassing material selection, controlled pultrusion processing, and standardized mechanical testing, a comprehensive evaluation of the process, property relationships governing carbon fiber/epoxy pultrusion was achieved. The experimental framework enabled reliable identification of the key parameters required for stable production and high-quality composite performance.

2.2. ASTM D3039

In this study, the tensile properties of carbon fiber/epoxy composite plates were determined in accordance with ASTM D3039/D3039M – Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials**.** ASTM D3039 is the most widely used method for reliably and repeatably measuring the in-plane tensile properties of polymer matrix composites reinforced with continuous or discontinuous high-modulus fibers. The primary objective of this standard is to obtain standardized mechanical properties that can be used in material specifications, quality assurance processes, R&D studies, and structural design analyses. One of the most significant contributions of ASTM D3039 is its ability to ensure the comparability of tensile test results performed on different material systems and in different laboratories. In this way, the effects of fiber–matrix compositions, manufacturing methods, fiber orientations, or environmental conditions on tensile behavior can be analyzed scientifically and with high reliability.

These procedures ensured the international comparability of the obtained tensile data, thereby enabling a reliable assessment of the mechanical performance of the composite system.

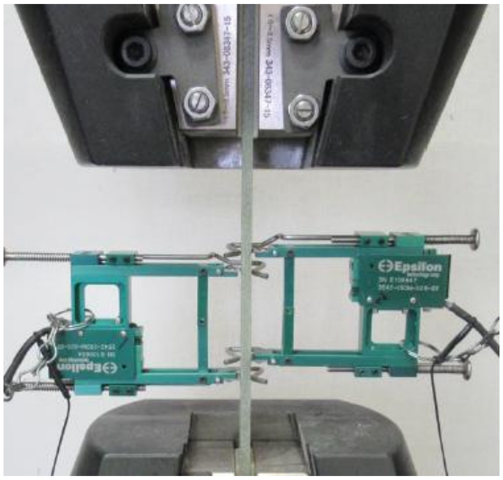

Figure 2. Tensile Test(ASTM D3039)

3. Results

The results of the experimental pultrusion trials demonstrated that relatively small adjustments in process parameters produced significant changes in flow stability, surface quality, and mechanical performance of the carbon fiber/epoxy composites. Early trials conducted with the initial heating zone positioned too close to the die entrance resulted in premature gelation and the formation of a white powder-like residue on the surface. This behavior, combined with low pulling speeds (18 cm/min), caused insufficient resin mobility and poorly consolidated surfaces. Rod-type specimens produced under these unstable conditions, exhibited comparatively low tensile strengths in the range of 1100–1500 MPa, along with brittle fracture characteristics indicating inadequate curing and fiber–matrix interaction. Shifting the first heating zone 15 cm backward significantly reduced entrance-region gelation, eliminated localized resin burning, and provided a more uniform thermal gradient. Increasing the pulling speed to 30–35 cm/min led to optimal shear-driven wet-out and minimized fiber congestion within the 5.5 mm preformer. Under these stabilized conditions, surface finishing improved noticeably, with reduced resin backflow and lower filament breakage. These improvements were reflected in the rod samples, which exhibited more consistent tensile performance and improved fracture morphology relative to the earlier trials. Fiber volume ratio (FVR) strongly influenced the consolidation quality. The 65–70% FVR range provided stable flow and uniform impregnation, while 72% FVR initially produced a smoother surface due to tightly packed fibers but later caused increased flow resistance, localized pressure spikes, and fiber clustering. This instability reduced the mechanical performance and increased scatter in the rod specimens produced at this high FVR level. A clear improvement was observed when transitioning from other fibers to the Tansome carbon fiber. Tansome rovings exhibited fewer filament breaks at the die entrance and more stable behavior in the wet-out region, leading to an overall improvement in process stability. Specimens manufactured under the optimized parameter window—30–35 cm/min pulling speed, 65–70% FVR, repositioned heating zone, Huntsman epoxy resin, and 5–7–5.5 mm preforming configuration—resulted in well-consolidated flat plates with tensile strengths reaching ~2300 MPa. These values are consistent with high-quality unidirectional CFRP laminates and reflect effective load transfer between fiber and matrix. Overall, the mechanical test results correlated strongly with the stability of the manufacturing process. Conditions that minimized resin backflow, suppressed early gelation, reduced fiber filament damage, and improved impregnation resulted in higher tensile strengths and more uniform failure patterns. Conversely, process conditions that promoted congestion, excessive resin viscosity, or premature curing yielded lower strength values, surface defects, and high scatter.

3.1. ASTM D3039 Tensile Test Results

Table 1. Pultruded Plate Tensile Test Results

Sample	Max Load (kN)	Tensile Strength (MPa)	Modulus (GPa)
1	49,81	2692,2	158,723
2	56,66	3062,83	154,249
3	56,6	3046,07	166,343
4	54,73	2932,4	159,282
5	55,79	3098,55	158,642
Average	54,718	2966,41	159,448
Std Dev	2,8527	165,417	4,352

Table 2. Pultruded Plate Tensile Test Results

Sample	Max Load (kN)	Tensile Strength (MPa)	Modulus (GPa)
1	45,12	2432,003	154,122
2	35,50	1945,994	161,956
3	41,40	2277,442	151,557
4	43,82	2430,366	159,021
5	44,96	2478,536	159,586
Average	42,16	2312,87	157,248
Std Dev	4,009	218,69	4,270

Table 3. Pultruded Rod Tensile Test Results

Sample	Max Load (kN)	Tensile Strength (MPa)	Modulus (GPa)

1	45,54	2438,53	163,34
2	46,93	2502,95	163,2
3	44,37	2338,5	158,9
4	43,02	2275,98	165,94
5	48,33	2531,81	165,13
Average	45,64	2417,554	163,302
Std Dev	2,0849	108,489	2,724

Table 4. Pultruded Rod Tensile Test Results

Sample	Max Load (kN)	Tensile Strength (MPa)	Modulus (GPa)
1	47,94	2517,95	172,16
2	47,19	2506,65	156,09
3	45,31	2431,35	165,24
4	49,53	2657,43	163,93
5	45,57	2404,82	165,78
Average	47,108	2503,64	164,64
Std Dev	1,7438	98,56	5,7406

4. Discussion and Conclusion

The experimental findings clearly demonstrate that the pultrusion process for carbon fiber/epoxy composites is highly sensitive to variations in thermal, kinematic, and geometric parameters. The strong correlation between process stability and mechanical performance highlights the importance of precisely balancing fiber wet-out, resin rheology, and die thermal behavior. The repositioning of the first heating zone played a critical role in reducing premature gelation, a phenomenon widely reported in pultrusion literature for highly reactive epoxy systems. By shifting the heating zone 15 cm backward, the thermal gradient at the die entrance was moderated, enabling the resin to remain mobile for longer and improving fiber alignment and consolidation. Similarly, maintaining pulling speeds in the 30–35 cm/min range ensured an optimal balance between shear-driven impregnation and residence time within the die. Lower speeds resulted in excessive residence time, leading to premature cure onset, while higher speeds (e.g., 45 cm/min) induced significant resin starvation and congestion within the final preformer. These findings are consistent with classical pultrusion models, which indicate that pulling speed scales directly with both heat transfer rate and the kinetics of the curing reaction. The influence of FVR further underscores the delicate balance required between mechanical performance and processability. Although higher FVR values, approaching

72%, theoretically enhance stiffness and ultimate strength, they also reduce resin channel size and increase internal pressure, heightening the risk of fiber clogging and uneven resin distribution. The optimal FVR range of 65–70% observed in this study aligns well with industrial pultrusion practices for CFRP rods and profiles. Fiber type also significantly affected process robustness. The improved handling and reduced filament breakage associated with Tansome fibers contributed to more consistent consolidation and higher tensile performance. This reinforces the importance of fiber surface quality, rovings' internal cohesion, and consistent tension control mechanisms that directly influence the microstructural integrity of the composite. Overall, the results emphasize the need for an integrated optimization framework in pultrusion manufacturing. Adjustments to thermal zones, pulling speed, resin viscosity, preformer geometry, and fiber selection cannot be treated independently; instead, they interact synergistically to dictate the stability and quality of the final composite. The systematic approach adopted in this study enables clear identification of optimal operating conditions and provides a robust foundation for scale-up and future process automation.

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